IDENTIFICATION OF COST EFFECTIVE INSPECTION STRATEGIES BY MEANS OF TAILORED QUALITY TOOLS, COST MODELING AND SIMULATION

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A dissertation submitted to the Faculty of Engineering of the University of Porto for the degree Doctor of Philosophy (Ph.D.) in Leaders for Technical Industries of the MIT Portugal Program

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Abstract

Delivering high quality products is key for successfully competing companies in global markets. Apart from well-defined customer needs high quality products are a consequence of stable manufacturing processes and sound inspection systems. Although aspiring Zero Defects, it remains only a theoretical objective in manufacturing. Failing manufacturing processes paired with inspection errors implies product delivery with nonconformities to customers with inestimable consequences. This is why companies allocate part of their limited budget to investments in (1) process improvement, (2) better product appraisal or (3) a mixture of both.

Process improvement may be achieved with the application of quality tools. But complex processes and specialized companies of different industries demand tailored tools. To imperfect manufacturing processes companies find remedies by installing huge product inspection, often upon the entire production volume. With regard to product inspection companies have the choice between three strategies: (1) single inspection, (2) re-inspection of rejected parts and (3) re-inspection of accepted parts. Each strategy implies different consequences on total quality costs. But, if a cost effective strategy is found there may be the need to deviate from it if quality improvement according to progress functions takes place.

A methodology is presented which integrates the prioritization of alternatives, cost models, progress functions and simulation. This serves the purpose to determine conditions of a favorable inspection strategy if progress ratios can be assumed for (1) process improvement or (2) better product appraisal. Case studies of the automotive industry are examined by using the elaborated methodology. Results indicate that the prioritization of individual nonconformities to be selected for quality improvement projects with the consideration of progress effects, determine the region of a favorable, cost effective manufacturing inspection strategy. Choosing the right quality improvement option contributes to the minimization of total quality costs. Moreover, the choice of a right inspection strategy should be reconsidered after improvement projects are concluded.

This thesis presents work to compliment and extend the scientific knowledge on the topic of total quality management. Both formal methodologies and practical modeling tools are provided to be applied by practitioners such as quality engineers from different manufacturing industries.

Resumo

A oferta de produtos de alta qualidade é um objetivo chave para as empresas competitivas em mercados globais. Para além da necessidade de terem as necessidades dos clientes bem definidas, produtos de alta qualidade são uma consequência de processos de fabricação estáveis e sistemas de inspeção fiáveis. Embora altamente ambicionada, a produção com Zero Defeitos é considerada apenas uma realidade teórica. As falhas nos processos de manufatura e erros nas inspeções implicam por vezes a entrega de produtos não-conformes a clientes. Este facto terá por vezes consequências inestimáveis. É por causa desta razão que empresas alocam uma parte do orçamento a investimentos em (1) melhoria do processo, (2) melhor vistoria do produto, ou (3) uma mistura de ambos.

A melhoria do processo é possível através da aplicação de ferramentas da qualidade. No entanto, processos complexos e empresas especializadas exigem ferramentas da qualidade customizadas às suas necessidades. De forma a remediar processos de manufatura imperfeitos, são efetuadas inspeções a um grande volume de produto, por vezes aplicadas a todo o volume produzido. As empresas escolhem entre três estratégias de inspeção: (1) inspeção única, (2) reinspecção de componentes rejeitados, ou (3) reinspecção de componentes aceites. Cada estratégia terá um impacto diferente nos custos de qualidade total. No entanto, no caso de ser encontrada uma estratégia eficiente em termos de custo, poderá mesmo assim haver a necessidade de a alterar devido a melhorias do processo subjacentes à curva de aprendizagem do processo produtivo.

É apresentada uma metodologia que integra a priorização de alternativas, modelos de custo, curvas de aprendizagem e simulação. Esta metodologia possibilita a determinação de características de uma estratégia de inspeção favorável, dado que os rácios de progresso possam ser assumidos para (1) a melhoria do processo ou (2) a melhor avaliação do produto. Casos de estudo da indústria automóvel são analisados implementando esta elaborada metodologia. Os resultados indicam que a priorização individual de não-conformidades a serem selecionadas para projetos de melhoria de qualidade com a consideração de efeitos de progresso, determina a região de uma estratégia favorável com um custo eficiente. A escolha da opção correta de melhoria de qualidade contribui para a minimização dos custos de qualidade total. Adicionalmente, a escolha correta de uma estratégia de inspeção deverá ser reconsiderada depois da conclusão de projetos de melhoria.

Esta tese apresenta um trabalho que visa complementar e estender o conhecimento científico do tópico da gestão de qualidade total. São fornecidas metodologias formais e ferramentas de modelação que podem ser de utilizadas, na prática, por engenheiros de qualidade provenientes de várias indústrias.

Kurzfassung

Die Auslieferung fehlerfreier Produkte ist essentiell für Produktionsunternehmen die erfolgreich am globalen Markt agieren. Nach sorgfältig identifizierten Kundenbedürfnissen sind qualitativ hochwertige Produkte ein Resultat robuster Fertigungsprozesse und fehlerfreier Inspektionssysteme. Obwohl eine Null-Fehler-Produktion angestrebt wird, bleibt diese oftmals nur ein theoretisches Ziel der Produktionsunternehmen. Instabile Fertigungsprozesse und Inspektionsfehler führen zur Auslieferung von Produkten mit Mängeln an die Kunden. Dies kann unvorhersehbare Konsequenzen mit sich bringen. Daher werden beschränkte finanzielle Ressourcen für (1) kontinuierliche Verbesserungsmaßnahmen, (2) die Verbesserung der Produktinspektion, oder (3) eine Kombination dieser Alternativen zur Verfügung gestellt.

Eine Prozessverbesserung kann durch die Anwendung von Qualitätswerkzeugen erreicht werden. Für ihren Einsatz müssen sie jedoch an die Komplexität und Spezialisierung der jeweiligen Industrie der Unternehmen angepasst werden. Instabilen Fertigungsprozessen wird mit einer Produktinspektion entgegnet, die sich oft auf das gesamte Produktionsvolumen bezieht. Den Unternehmen stellen sich drei Alternativen zur Produktinspektion: (1) Die einmalige Inspektion, (2) die wiederholte Inspektion abgelehnter Artikel und (3) die wiederholte Inspektion akzeptierter Artikel. Allerdings hat jede der drei Strategien eigene Konsequenzen für die Gesamtqualitätskosten. Ist jedoch eine kosteneffektive Strategie bestimmt worden, so muss eventuell von ihr abgewichen werden, soweit bei der Qualitätsverbesserung von Lernkurveneffekten ausgegangen werden kann.

Die Gesamtmethode umfasst die Priorisierung von Alternativen, Kostenmodellierung, Lernkurven und Simulation zur Bestimmung der Bedingungen vorteilhafter Inspektionsstrategien. Des Weiteren werden Lerneffekte für (1) Prozessverbesserung oder (2) verbesserter Produktinspektion berücksichtigt. Zur Revidierung der erarbeiteten Methoden werden Fallstudien aus der Automobilindustrie herangezogen. Die Resultate zeigen, dass die Priorisierung einzelner Fehlertypen die vorteilhaften und kosteneffektiven Produktinspektionsstrategieregionen beeinflussen. Maßgeblich dafür ist das Eintreten von Lerneffekten zur Beseitigung der Fehlertypen bei der Auswahl der Qualitätsverbesserungsprojekte. Die Wahl der richtigen Verbesserungsoption trägt zur Qualitätskostenminimierung bei. Allerdings sollte die Entscheidung für eine Inspektionsstrategie nach Beendigung des Qualitätsverbesserungsprojektes erneut überprüft werden.

Diese Dissertation leistet einen Beitrag zur Erweiterung des Wissenstandes im Themenbereich des Total Quality Managements. Formalisierte Methoden und modellierte Werkzeuge wurden zur konkreten Anwendung entwickelt. Insbesondere können Sie von Qualitätsingenieuren aus verschiedenen Fertigungsindustrien eingesetzt werden.

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List of Acronyms

ABC	Activity-Based Costing
CoC	Cost of Conformance
CoNC	Cost of Nonconformance
CoQ	Cost of Quality
CWQC	Company-Wide Quality Control
DC	Decision to be conforming
DES	Discrete Event Simulation
DM	Data Mining
DNC	Decision to be nonconforming
FMEA	Failure Mode and Effect Analysis
FT I / FTII	Failure Type I / Failure Type II
HHI	Herfindahl-Hirschman Index
KDD	Knowledge Discovery in Databases
NC	Nonconformity
NOK	Not OK
OK	OK
PAF	Prevention, Appraisal and Failure
PBCM	Process Based Cost Model
SBU	Strategic Business Unit
TDABC	Time-Driven Activity-Based Costing
TPS	Toyota Production Systems
TQM	Total Quality Management

List of Symbols

APD	Average Production Days
A	A set consisting of all occurring NCs
a	Number of labor hours for first unit production
α	Inspection error of conforming parts
b	Learning index
β	Inspection error of nonconforming parts
C, c	Cost
CRF	Capital recovery factor
CI	Capital investment
CU	Capacity Supplied
ccr	Capacity Cost Rate
ccs	Cost of Capacity Supplied
cdr	Cost Driver Rate
cpd	Closedown period in days
cpw	Closedown period in weeks
CI	Capital investment
CT	Cycle time
d	Reduced defect level
DPP	Days per period
DPY	Days per year
δ	Conforming items
e^2	Squared error
ε	Re-inspection process rate
f	Fraction
γ	Rework process rate
h	Number of labor hours

HPS	Hours per shift
int	Interest rate
$invp$	Investment in prevention activities
κ	Conforming re-inspected items
l	Number of employees
L	Length of time
λ	Production rate
μ	Inspection process rate
M	Set of selected NCs
n	Number
N	Natural numbers
NoS	Number of shifts
η	Non-conforming re-inspected items
O	Set of unselected NCs
OP	Own capital
p	Progress ratio
$pcrs$	Practical Resources Supplied
PB	Paid breaks
q	Probability
r	Interest rate
R	Rework rate
Rec	Recoverability after rework
s	Market share
S	Scrap rate
SDC	Sub division costs
t	Time
$TCCC$	Total cost center costs
v	Weighting factor

V	Production volume
w	Weighting factor
W	Wage
WPY	Weeks per year
WS	Work station

CHAPTER 1

1 Introduction

Today's market requirements are demanding. They are characterized by shorter product life cycles, higher product variation and complexity, and global competition. Furthermore, one can notice a shift from mass production to mass customization. It is not enough to merely be able to produce something and make it work. It is more about the distinct features of a product to increase value in the perspective of the customer. Additionally, products must be safe when in operation. They must be reliable and match safety regulations.

The shift from a supplier dominated marked to a demand driven market entailed increased customer requirements and the need for precision to produce reliable products. This is particularly true for products, which concern customer's safety and cannot fail in use. Thus, quality related topics gained of importance and its domination is a key factor for competitive advantage.

The developments in this thesis target to present an approach to foster a more informed decision making process of quality improvement project selections in manufacturing companies. The developments are supported by case studies of a real world manufacturing company from the automotive industry. The approaches can be used by practitioners such as quality engineers and be applied in other industries. Tools and simulation models are developed to assist in quality improvement projects. Furthermore, cost modeling approaches are explored to provide guidance during development projects of to-be manufacturing systems. Elements of the developed tools and cost models are used in a methodology to identify favorable manufacturing inspection strategies.

1.1 Context

Delivering high quality products entails to best derive from customer needs tangible characteristics. These characteristics must be translated and epitomized by the product and its features. Products free of nonconformities is a status ambitiously sought. Complex global supply chains with demanding manufacturing processes of different degrees of automation and manual work tasks can be driver for quality issues. Decreased time for product development, increased customer requirements and the need of a high customization of products embedded in an intense market competition amplify quality issues. This implies high technological standards for manufacturing and the adoption of process and quality control. On the other hand a high degree of capacity utilization is mandatory to assure cost efficiency. This is confined by set-ups, for product variety, or maintenance, for better quality. Hence, one can find often trade-offs between production volume maximization, product variety and quality.

This is particularly true for suppliers of the automotive industry that manufacture high technological products. Some of them are characterized with multidisciplinary production processes, which involve various scientific disciplines. Leveling mass production with a high variety of specifications is the challenging task for the exigent product that is responsible for safety and high performance at the same time. It is of great importance to not deliver the product with nonconformities since it is tightly tied to the customers' safety.

Nonconformities can be detected prior to shipment at an inspection stage or at the customer and may return as claims. Non-conforming products delivered to the customer can cause inestimable damage. Not only replacing or repairing the product is costly but also losing the customer for future business is at stake. The damage caused by delivered nonconforming products is barely estimable. This is why companies strive for reaching a status of Zero Defects to avoid penalties by customers. But Zero Defects is a target that is not always achievable in an industrial environment. Thus, one aims to either reduce the number of nonconforming products that reach the customer, the overall occurring numbers of nonconformities (NCs) at the manufacturing processes or both. Reducing the number of delivered products with NCs can be achieved in two ways: Firstly, by reducing the occurring number in the production plant in general or secondly, by increasing the effectiveness of the inspection process. Both cases imply investments. In the first case one has to invest in improving the manufacturing process. In the second case investments in ameliorating the inspection process take effect.

A lot of companies establish Total Quality Management (TQM) as a management system. They deploy the values, tools and techniques of which TQM is equipped with to change their company culture. The aim is to adopt a spirit of satisfying the needs of the internal and external customer. Other established systems are Lean Thinking and Six Sigma. Lean Thinking targets to increase the efficiency through the elimination of waste and Six Sigma provides with statistical tools and metrics to reduce variability in the production processes. These concepts aim to increase process efficiency. But product inspection is barely covered by the previously mentioned areas. In order to determine an inspection strategy companies are not always aware of the quality cost concept. Their primary decision criterion is reducing process and scrap costs. However, a holistic view of quality costs of product inspection includes acknowledging fallibility of the inspection system. This fallibility can be analyzed and expressed in costs to determine the most appropriate inspection strategy.

However, there is no integrated approach that allows a quantitative analysis to enhance the informed decision making. The research in this thesis derives from the selection of individual NCs cost effective inspection strategies. Furthermore, recommendations of improvement options are given based on the anticipation of progress ratios due to progress effects.

1.2 Motivation

The presented context is specifically true for a real manufacturing company, with which the author collaborated during the thesis development. The company is a mature producer of a high technology product integrated in the supply-chain of the automotive industry. The environment of the different manufacturing processes is similar to mass production that considers mass customization to target satisfying different customer segments' needs. They produce an important part of the automobile. It is related to driving performance characteristics and passenger's safety. The product affects customer safety and maintaining a high quality level is of paramount importance. A quality management system certified according to various standards such as DIN EN ISO 9000, DIN EN ISO 9004 and ISO/TS 16949 relates to all business and operating processes.

A humanly based inspection system is placed at the end of the manufacturing line. The inspection is done based on 100% of the production volume. The types of nonconformities are registered and categorized at the inspection system. Up to a certain degree of nonconformance products can be reworked and if successfully recovered considered as conforming. More severe nonconformities must be scrapped. The company strives to improve process quality to increase customer satisfaction (driving performance characteristics and safety) and to reduce costs for scrapping or reworking products.

The company uses brainstorming approaches and initiates investigations for quality improvement. The primary focus lies on reducing scrap rates of specific NCs. Typically they form multi-departmental teams for quality improvement projects. But root cause identification has proven to be difficult, which is why several approaches in this thesis were developed.

A six months internship in the form of a full time placement was done to get inspired by recent problems of the manufacturing company under investigation. The research work was dedicated to test and develop approaches to support the decision making process of identifying a cost effective inspection strategy considering improvement options. To better quantify the as-is situation novel approaches were developed. The results achieved in this thesis help solving the identified problems and also fill gaps in the scientific knowledge. They can also be applied by practitioners such as quality engineers and be used in other industries than the automotive industry.

1.3 Research Objectives

The objective of this research is to extend existing methods to enhance the informed decision making process of industrial companies with regard to quality related topics. More specifically, the research addresses manufacturing process improvement and the identification of cost effective regions of inspection strategies when considering a fallible product inspection system. This includes novelistically developed methods of nonconformity root cause analysis and the prioritization of nonconformities upon multi-attributes to be selected for future improvement projects. In addition to that, the use of detailed simulation models of a company’s reality show how to eliminate blockages of manufacturing processes due to human variability and the impact of quality cost reduction of different improvement options. The aforementioned developments are coupled to provide an integrated approach in order to provide guidance for the selection of a cost effective inspection strategy. The analyzed inspection strategies are single inspection, re-inspect rejected parts and re-inspect accepted parts. After the cost effective regions of the strategies are found the analysis focuses on the selection of quality improvement options. It is analyzed which improvement option will have the greater effect on the cost beneficial regions of the inspection strategies. The improvement options set focus on individually selected nonconformities and improvement takes place gradually according to progress ratios of a well-known progress function. One improvement option is investments in prevention activities in order to improve continually previous manufacturing processes to prevent the previously identified nonconformities from occurring. The other improvement option is investments in appraisal activities in order to tighten the effectiveness of the inspection for a better detection of the previously identified nonconformities. Finally, different progress ratios are taken in order to show the cost beneficial areas of choosing one inspection strategy over the other. The integrated approach results in an inspection strategy map that presents the cost beneficial regions with regard to nonconformance rates, progress ratios and penalty costs (of nonconforming product delivery). This enables to take two decisions: Firstly, one can select the cost beneficial inspection strategy based on a given quality level and penalty costs. Secondly, one can select the type of improvement option that promises the greater cost benefits for the individual inspection strategies.

The study is separated in two areas and accordingly to the areas the research questions (RQs) are presented. The first one concentrates on the development of tools to quantify and better understand the as-is situation and to improve manufacturing processes:

RQ #1: How to identify possible root causes of nonconformities of different production process steps with a product appraisal placed at the end of the manufacturing line?

RQ #2: Based on a number of nonconformities, what can be relevant attributes to select nonconformities that ought to be selected for a future improvement measurement?

RQ #3: How to rectify the effect of unscheduled human variability of an inspection process, which is subsequent of a continuous process?

The second area of the study focuses on the identification of cost effective inspection strategies. The costs consider total quality costs and process costs of different inspection system configurations, which are estimated through cost modeling techniques.

RQ #4: How to model quality related costs to foster their use for decision-making?

RQ #5: If a best inspection strategy is identified, is there the need to deviate from it if improvement according to progress functions takes place?

1.4 Research Methodology

The research process was performed in a deductive approach as presented in Figure 1. After an internship at one plant of the affiliated company ideas were generated and needs for action identified. The next step was to consult literature to understand what has already been developed and investigated in order to solve identified problems. After matching the ideas and need for action with the findings in literature theories were established and new models built. Relevant data was collected and input into the models in order to validate the established theories. Based on the observed relationships the conclusions were drawn.

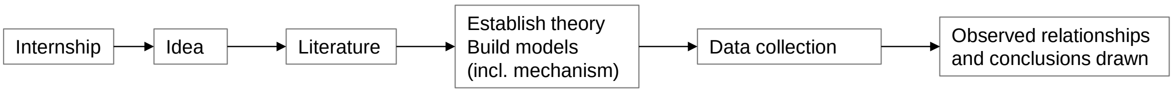


Figure 1: The thesis research methodology.

Figure 2 presents the choice of method for developed elements in this thesis. Hereby, the elements are developed tools or models in order to answer the presented research questions. For each of the elements of development it is presented the choice of research method, the population, the operationalization, the data analysis and the generalizability.

Element of development	Choice of research method	Population	Operationalization	Data analysis	Generalizability
3.2.2 Root Cause analysis	Existing data research, formal modeling	Quality and process related data of the affiliated Company	Proposed method/ quality tool	Quantitative/ statistical (case studies)	Possible for similar contexts
3.2.3 Portfolio Prioriti-zation	Existing data research, interviews, formal modeling	Quality and process related data of the affiliated Company	Proposed method/ quality tool	Qualitative/ Quantitative (case studies)	Possible for any portfolio decision making problem
3.3 Simulation	Experiments (in simulation)	Depiction of the companies reality	Simulation model and sensitivity analysis	Quantitative (case studies)	Limited due to a customized simulation model
4 Cost modeling	Formal modeling, Existing data research	Cost data of the affiliated company	Cost models, cost system	Quantitative (case studies)	- limited to customized cost models; - possible for the new proposed approach
5 Integrated approach	Formal modeling, Existing data research, interviews	Cost, quality and process related data of the affiliated Company	Proposed method	Quantitative (case studies)	Possible for a similar context

Figure 2: Research methods of elements of the thesis.

"Root cause analysis" (presented in section 3.2.2) and "portfolio prioritization" (presented in section 3.2.3) are both developed quality tools. They can be applied to similar contexts or for any portfolio decision making problem. Existing data research and formal modeling are used on quality and process related data of the affiliated company. Case studies are presented to validate the proposed methods.

Furthermore, experiments are done in simulation (please refer to section 3.3), which depict the affiliated company's reality and allow performing sensitivity analysis. Case studies are presented to draw conclusions. The conclusions are insightful to the presented context but are limited in generalizability due to the customized simulation models.

Different cost modeling styles performed on existing data of the affiliated company enables to perform sensitivity analysis (please refer to section 4). Results are limited in terms of the generalizability due to customized cost models. But a novel proposed approach can be used to explore impacts on costs in new dimensions of the analyzed system.

The integrated approach (please refer to section 5) presents formal modeling on existing cost, quality and process related data of the affiliated company. The proposed method is validated with a presented case study and can be applied for problems in similar contexts.

1.5 Thesis Structure

The overall thesis structure is illustrated in Figure 3. The map shows all interrelated topics and elements, which can be used as a guideline for the thesis interpretation.

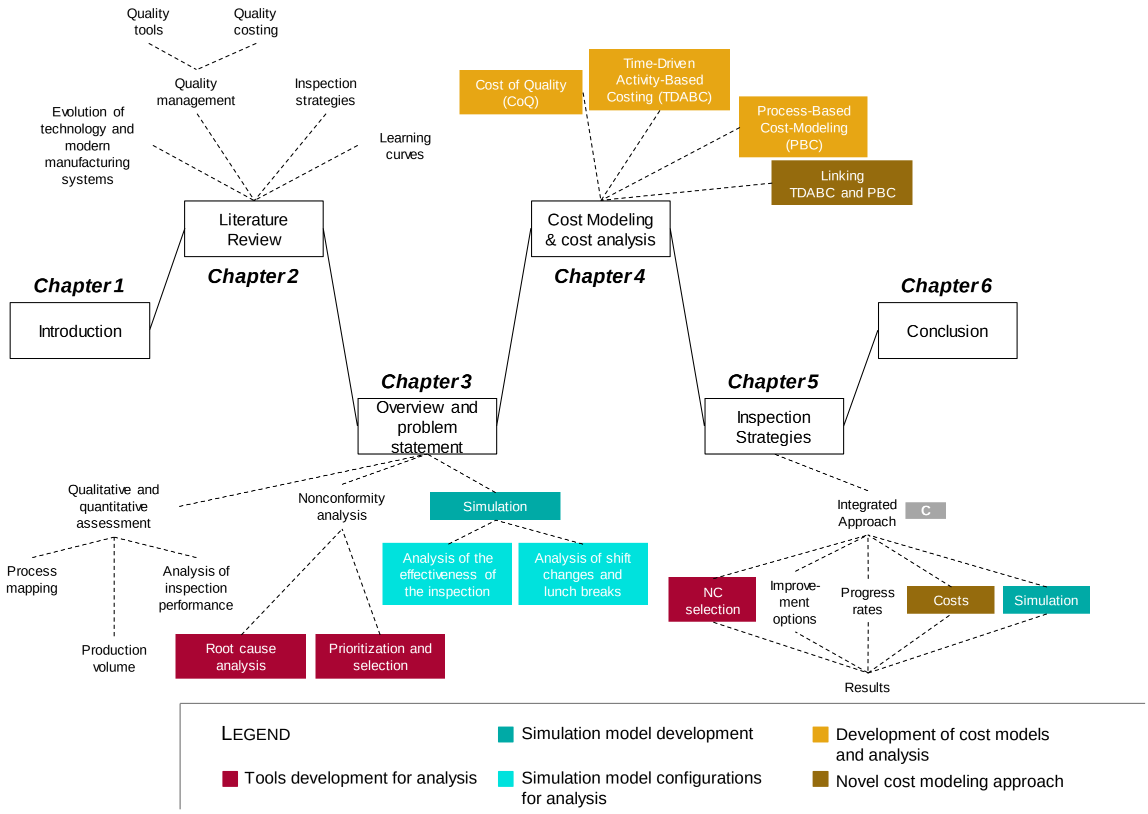


Figure 3: The thesis structure.

In the first chapter context and motivation are discussed, the research objectives and methodology presented and the thesis structure outlined. Relevant literature is presented in the second chapter and a background for the thesis is established.

Chapter 3 presents the overall as-is situation of the affiliated company's inspection system. Hereby, relevant indicators of the manufacturing performance are quantified and a process map given. The nonconformities, which occur at the inspection system, are studied and two novel approaches are presented. One identifies possible root causes of NCs of single machines of two consecutive process steps. The other one deals about the prioritization of the most relevant NCs to be selected for future improvement options. Each approach suggests a methodology and its formalization together with result presentation in the form of a case study from the affiliated company. Moreover, a discrete event simulation model is used to analyze the production process in two ways: Firstly, the effectiveness of the inspection is analyzed and its impacts on quality related cost identified. Secondly, the company's human inspection system is analyzed upon bottleneck situations. This is followed by proposed measures to improve this process and validated by means of simulation.

Chapter 4 deals about three different cost modelling techniques. Firstly, cost gathering exercises are executed to estimate quality related costs. This serves twofold, as analysis according to the PAF allocation method and as input for another cost modeling technique, the Time-Driven Activity-Based Costing (TDABC). By means of the TDABC method the capacity utilization of cost centers are determined and improvement suggestions given. Additionally, a to-be manufacturing system is expressed as costs according to the Process-Based Cost-Modeling approach. Cost consequences of different operational conditions are discovered. In order to use costs for the integrated approach that determines cost effective inspection strategies a novel cost modelling approach is proposed. PBCM and TDABC are aggregated and form a new approach to model costs. With PBCM process and investment costs of new inspection system configurations are estimated. TDABC determines the activity costs for those new inspection system configurations. In that way one single activity of a to-be system can be expressed as costs. Those activity costs are key elements for the integrated approach in chapter 5.

Chapter 5 presents an integrated approach to identify favorable inspection strategies and an improvement option with considered progress ratios. Therefore, simulation models are developed, which depict the inspection strategies. Results are connected to costs to generate a strategy map that outlines the regions of favorable inspection strategies according to parameters. The integrated approach is composed of components, which are developed in the previous chapters. Namely, these are elements of the developed cost models (chapter 4), the prioritization and selection of NCs (chapter 3) and root causes analysis (chapter 3).

In the sixth chapter conclusions are drawn and future research outlined.

CHAPTER 2

2 Literature Review and Foundations

In this chapter the foundation of the thesis is built and a literature review of relevant topics given. An overview of the historical development of technology and modern manufacturing systems is presented. The topic of quality management is discussed with emphasizes on quality tools and quality costing. Furthermore, inspection strategies and learning curves (progress functions) are introduced.

2.1 Evolution of Technology and Modern Manufacturing Systems

Alongside with the history of mankind manufacturing evolved together with technical advances. It was technological advances that provided mankind with a greater variety of food by building tools for hunting and agriculture. Technology even decided over winning wars between tribes or countries. McNeil [1] correctly encourages studying the history of technology in order to learn from it. First attempts to classify the archeological ages based on technology were done by Thomsen [2]. Studying the tools and weapons of the earliest inhabitants inspired him to classify the three ages into the materials they used: Stone, Bronze and Iron. These ages are generally accepted complemented with the Copper Age in between the Stone and Bronze Ages. McNeil [1] reports that in the field of archaeology it was proposed to regard pre-history as a history of technology. In this perspective the event line should be rather organized by the rise and fall of technologies, such as hunting and weapon-making, herding and domesticating animals, crop-growing and agriculture, pottery and metal working instead of the rise and fall of civilizations. Having this in mind, nowadays, it is generally accepted to divide the technological ages of man in several eras with overlapping periods [1]: (1) man, the hunter, masters fire; (2) the farmer, the smith and the wheel; (3) the first machine age; (4) intimations of automation; (5) the expansion of steam; (6) the freedom of internal combustion; (7) electrons controlled. Table 1 lists the technological progress and their timelines of the technological ages. It also presents how work was structured as early manufacturing techniques.

Table 1: The technological ages of man with technological progress and their structure of work.

Date	Technological Age	Technological Progress	Structure of work
10 million ybp | BC 1,500	(1) Man, the hunter, masters fire	Tools and weapons made of wood, bone and stone; Induction of fire Material ages: Stone 10 million ybp – 3000 ybp; Bronze 3,000 to 1,500 BC; Iron Age started 1,500 BC	First degree of specialization Skilled occupation by long practice and experiments
BC 10,000 | AD 1000	(2) The farmer, the smith and the wheel	Cultivation of bread wheat; Pottery wheel Tools and jewelry made of copper, bronze and Iron: Furnace, crucible, blowpipe Trades on wheels and ships on rivers and sea Plough for agriculture First machines: lever, wheel and axle, wedge, pulley, screw (Egyptians); Cast iron, paper making, gunpowder (Chinese); Roman mill, water supply (Romans); Spinning wheel	Skill and knowledge of a person; specialization and division of labor: Metal workers are specialists who need special equipment and depend on farmers to provide them with tools
1300 | 1700	(3) The first machine age	Clocks (standalone and portable), mint work, telescope, crank, printing of books	
1000 | 1850	(4) Intimations of mass production	Coinage and mint work Locks, flints, automatic windmill	First mass production: Clay molds, screw press, rolling mills, knuckle press Forerunners of factory system: Steam engine or water wheel powered to drive a number of machines Interchangeability of components to manufacture Labor division into sections to make different parts instead of one specialist
1350 | 1900	(5) The expansion of Steam	Steam engine: Railway, shipping to accelerate news	
1884 | 1903	(6) The freedom of internal combustion	Petrol engines and first cars to set basis of modern transportation and provider of freedom	
Since 1881	(7) Electrons controlled	Centralized power generation and distribution of power to every factory, home and office through mains Public lighting, radio, television, pocket calculators, computers, heart pacemakers, the maser and laser, CAD, solar cells, satellite communication, man and unmanned space travels, artificial intelligence	Automation and robotics Advanced manufacturing techniques

During the ages the use of technology began with man being a hunter and lighting fire. The forge of metal by craftsmen and the invention of the wheel eased farming and transportation. Basic weapons and tools were invented. First machines and devices such as cranks, telescopes and clocks appeared and the printed book endorsed the spread of knowledge. With the steam engine as a power source automation was introduced, with progress in mining, textile and metal working industries. The expansion of steam led to significant progress in railway and ships. Transportation of goods on a larger scale became possible along with the haulage of workforce from the countryside to the plants' locations. But it was the internal combustion and invention of the automobile, which contributed to a higher degree of freedom through individual mobility. It was exactly this industry which coined the recent era of manufacturing. Electrons controlled is the last technological age described by McNeil [1]. Power generation and the distribution of power provided the world with electricity and entailed tremendous change to the world. The electrification of industry, homes, transportation, business and entertainment with various applications endorsed the comfort, convenience and well-being.

The biggest contribution to modern manufacturing systems stem from the automotive industry, which provided the world with LEAN Thinking. Womack et al. [3] describe the transition to LEAN in different phases. In the point of view of production paradigms there was the crafts production system (around 1896), then mass production (around 1913) and finally LEAN Production (1990). Craftsmen were skilled workers who hand built cars based on customer specifications [3]. Due to the different customer specification and the lack of a standard gauging system made it impossible to produce two identical cars. This entailed the problem that the unit cost did not fall. A remedy to this brought Ford's mass production system. Womack et al. [3] understand the key of the system threefold: interchangeability of parts, simplicity and ease of attachment. Furthermore, Ford introduced the moving line and simple tasks were performed by workers. This system provides a higher productivity because with standardized tasks, standardized parts are assembled to produce a standardized car.

LEAN originated from the Toyota Production System, with main contributors Eiji Toyoda and Taiichi Ohno, and Total Quality Management (TQM). LEAN Thinking is embedded in LEAN Production and deals about the identification of the value in the eyes of the customer and the elimination of any waste that does not add value to the customer [3]. IT is miscellaneously describable such as a philosophy, a batch of principles and as a pack of practices based on a philosophy of eliminating waste within a product's value stream [4]. This is done by defining the value, identifying the value stream, make value flow and implement a customer initiated pull system. Additionally, the constant strive for perfection must become a virtue [5]. The practices are related with quality management, pull production, preventive maintenance, and human resource management [4]. Over time Toyota Production System became a competitive advantage of the Japanese car manufacturer over western manufacturers. It took western companies decades to identify LEAN principles and implement them in their own manufacturing systems [3]. Although, LEAN originated from the automotive industry it is transferred and implanted to other industries and also to services and business processes and is incorporated in every modern manufacturing system [5]. Quality concepts evolved from 1960 to 1990 and form Quality Assurance, which is the ancestor of TQM. It is generally accepted to describe TQM as a philosophy equipped with a set of tools and techniques with the target to increase customer satisfaction and continuous improvement. Having a mindset of satisfying the needs of the internal customer is achieved through tactics for changing a company's culture and structured technical techniques [6], [7]. In addition to the above mention philosophies Six Sigma is also widely implemented and in use. The Six Sigma concept was developed and introduced by Morotola and awarded with the Baldrige National Quality Award in 1988 [8]. Besides being a measure for process variation through capability it is also described as a philosophy for improvement with statistical tools and metrics [4], [9]. It is also related to reduce process errors within a process improvement initiative and many quality tools and techniques are applied [4] and [9].

Nowadays LEAN principles are adopted in companies' manufacturing systems but the level of implementation and detail varies between companies. In the German literature modern manufacturing systems are described as holistic manufacturing systems (Ganzheitliche Productionssysteme – GPS). Spath [10] assumes that three elements of origins form today's organizational models of manufacturers. Innovative types of employment, Taylorism and Lean Thinking are the three elements of origins [10]:

1. Innovative types of employment consider the employee as the central element and key personnel of the company. It is characterized by process-oriented independent concepts, self-dependent and self-organized team work and leadership by objectives. This concept transfers higher responsibilities to the employees.
2. Taylorism is the concept of maximizing the productivity aiming to deliver markets with mass produced products. There is a division in planning and executing the work:

Experts plan and labor executes. Furthermore, there is a high degree of division of labor and standardized work tasks.

3. Lean Thinking originates from the Toyota Production System in Japan after the World War II. Its key objective is increasing efficiency through the elimination of waste. Principles are Just-in-Time production, Pull Production, minimizing set-up times and methods are Kaizen (continuous improvement), TQM or Kanban.

After evaluating the three above presented models of organization Spath [10] concludes that each presents distinct strength and weaknesses. The right combination of the elements eliminates weaknesses and aggregates the strengths. This is exactly the purpose of devising a holistic manufacturing system.

Holistic manufacturing systems are socio-technical systems with standardization elements [11]. The holistic system is the combination of concepts of technical-organizational and personnel-organizational nature. These aim to harmonize man, technology, and organization in such a way to satisfy all the needs of the company's stakeholders. Holistic furthermore includes all elements of the company's value chain [11].

Gienke and Kämpf [11] report that there are five fields also referred to as modules identified, which structure a holistic manufacturing system: (1) Process and work organization, (2) standardization and visualization, (3) robust manufacturing processes (4) manufacturing/Logistic and (5) continuous improvement. These fields are the pillars of the holistic manufacturing systems as one can see in Figure 4.

Holistic Manufacturing System

Module	Working organization	Standardization visualization	Robust processes	Manufacturing/ Logistics	Continuous improvement
Principles and Objectives	• Clearly defined tasks and roles • Employee involvement • Transferring competencies and responsibilities to workers • …	• Standardized of methods and processes • Visualization • Ergonomics • …	• Process organization • Decentralization • Robust processes / products • Preventive quality management (defect prevention) • …	• Heijunka • Pull production • Just-in-Time • Continuous flow production • …	• Elimination of waste • CIP • Employee suggestions • …
Components	• Teamwork • Leadership • Management by objectives • Attitude surveys • Job description • On-the job training • Job rotation	• Standardized work flows • Standardized shift change • Standardized facilities • 5S • …	• Root cause analysis • SPC • Quality circles • Jidoka • FMEA • Automation • Poka-Yoke • Audit	• Fifo • Set-up times reduction • SMED • Small batches • Kanban system • Fixed takt time • …	• CIP workshop • PDCA – cycle • Creativity methods • Graphical process analysis • 5 whys • …
Tools	• Team boards with KPIs • …	• Andon-Board • …	• Control chart • SPC control charts • Ishikawa diagram • …	• Kanban • …	• Problem communication report • …

Figure 4: An example of a holistic manufacturing system (Ganzheitliche Produktionssysteme adapted from [12]).

The evolution of technology implied different approaches to structure work. Nowadays, LEAN and TQM principals and philosophies are embedded in modern manufacturing systems to ensure competitive advantage through customer focus and cost reduction by waste elimination. They are trans-industrially valid and are considered by most companies' quality initiatives.

2.2 The Evolution of Quality

Together with manufacturing systems the perspective on quality evolved. Figure 5 portrays the evolution of total quality management along time. Juran and Godfrey [13] explain the development of the focus on quality during the presented timeline:

Up until now some companies focus on product quality. During the product development phase companies prefer making the product work according to engineering requirements over customer requirements. Engineering requirements are also the criteria of the product inspection.

Crosby' [14] “Do it right the first time” is the spirit of the product process quality approach [13]. The belief holds that finding the error on a fully assembled product is more expensive than ensuring proper functionality of its parts. And therefore the assembly system must be controlled. By means of control charts along the production process the importance and reliance on the final inspection is reduced and manning can be released to perform other value adding tasks.

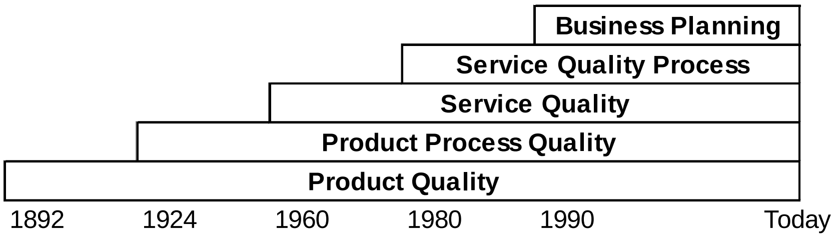


Figure 5: The evolution of total quality (adapted from [13]).

The next phase is no longer only dedicated to the functionality of the product rather it takes into account several other aspects of services accompanied to the product. Service Quality deals with additional provision of services such as repair and maintenance, order entry, billing waiting times, availability of spare parts, financing and leasing among others.

Service Quality Process considers the costs of providing quality services. Process improvement through industrial engineering tools such as cycle times, reducing number of steps or improving overall efficiency is accompanied with the consideration of costs.

In the more recent years the term Business Planning is more applied which is the integration of goals of quality management into financial goals. Quality goals are broken down in sub goals, periodical goals and projects. In that sense it is adopted as total quality management by companies and anchored as a system.

The term “Total Quality Management” firstly emerged by Nancy Warren who worked as a behavioral Scientist at the US Navy (Walton 1990, cited in [15]). The subject Total Quality Management (TQM) is extensive, diverse and influenced on a subjective body of thoughts. There is no global definition of TQM and companies often show highly diverse interpretations and level of implementations [15], [6] and [16]. In the Japanese literature [17] there can be also found Feigenbaum’s [18], [19] denomination of “Total Quality Control “as well as “Company-Wide Quality Control” (CWQC). Both are similar to the TQM approach whose term is widely spread among American managers [15]. Bounds et al. [15] also mention that there is a perception of the letters of TQM such as follows: “Total” comprises every employee of the company, “Quality” refers to brilliance in any regard of the company and “Management” relates to striving for quality results by a quality management process. They go on and highlight the strong focus on people and managers within TQM.

Although, there is no global definition of TQM there are several proposals for it in literature. All are similar in core but can have different attachments. In the view of the author TQM can be regarded as a philosophy with practiced values, which are anchored on every company level. It is furthermore equipped with a set of tools and techniques that targets to increase customer satisfaction and decrease costs through continuous improvement.

Since TQM is a philosophy the frame of definitions cannot be seen rigidly. Rather it shall be considered as a guideline for practitioners. Juran and Godfrey [13] state that the universally accepted goals of TQM are lower costs, higher revenues, delighted customers, and empowered employees. Rampey and Roberts [7] include besides the customers also the suppliers to be part of the TQM range and declare it as an integral part of high-level strategy. Hradesky [6] refines and understands the philosophy to be concentrated on satisfying the needs of internal customers by means of cultural-changing tactics and structured technical techniques.

In addition to the lack of a clear TQM definition in literature concepts what constitutes TQM also vary. This results to ambiguous proposals of concepts, techniques and components of TQM. Figure 6 shows the composition of elements of the Total Quality Management infrastructure. One of the key elements is the quality system which is best defined in ISO Standard 9004-1 [13].

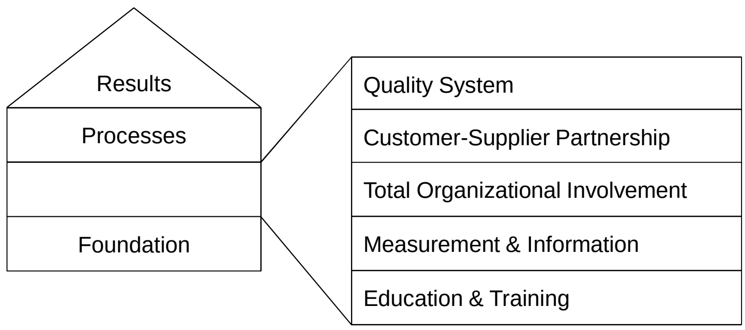


Figure 6: The total quality infrastructure (adapted from Leadership for the quality century, 1997, Juran Institute, Inc., Wilton, CT. cited in [10].

The quality system is considered as the most important one of the infrastructure. This may contain a customer supplier partnership striving for the partnerships designed by the Japanese automotive industry as a role model [13]. Womack and Jones [3] describe a case where a company vertically disintegrated in-house supply operations to first Tier supplier companies. However, they kept a share, which resulted in the company not to be completely separated. Furthermore they acquired shares from completely independent suppliers to foster a similar relationship and the suppliers acquired shares among each other. These relationships involve providing funding to each other, sharing operators and managers if needed and involving suppliers in the product development process. This resulted in a supporting, sharing and collaborating intertwined supportive network, which was considered to be mutually beneficial [3]. Similar to the previous supplier manufacturer relationship a network with fully or partly owned dealers was developed. They aimed to integrate the buyer into the development process by striving to keep customers for a lifetime through customer selling strategies and identifying promising buyers. And the dealer had to collaborate with the factory to adjust orders with the manufacturing sequence.

Juran and Godfrey [13] highlight the importance given to the employees. Companies have realized the benefit of improvement suggestions by employees or their participation in improvement and quality planning teams. In that way a total organizational involvement is achieved. Furthermore, they emphasize the education and training of the organization to work in teams. Hereby, the training targets on quality improvement projects and learning by doing is encouraged. Juran and Godfrey [13] also identify measurement and information to be relevant and having the right information is desirable.

In line with the definition of TQM likewise there is no unanimity of its components among authors. Bounds et al. [15] for example summon managers to go beyond TQM to make sure that they learn about the topics, concepts and methods that evolve by time within the rather new field of TQM. They define the components to be related to total quality infrastructure in Figure 6. To those components they point out that the design of critical business success factors, taken from tactical planning sessions. Furthermore, they recommend choosing projects, which directly influence these critical business success factors. Additionally, those projects should be high returns-on-investment, which bring the present state closer to the vision.

Generally accepted and well known are the three critical processes of quality management - *Quality Planning*, *Control* and *Improvement* - also referred to as the Juran trilogy [13]. *Quality planning* refers to identifying a quality planning roadmap, which is a universal sequence of events. After identifying the customers and their needs corresponding products and services are designed to match those needs. It is critical to involve the operating forces who are responsible of the plan and its realization. *Quality control* is based fivefold: A clear definition of quality; a target; a clear goal; a way to measure actual performance, a way to measure that performance; and the possibility to measure and compare with the target. Quality Control and Statistical Process Control are discussed topics in that area. The *Quality Improvement* process results in “breakthrough” changes achieved by individuals or organizations regarding performance levels.

Hellsten and Klefjö [16] give a well-structured categorization of the components of TQM. They understand TQM as “[…] a management system consisting of three interdependent components: Values, Techniques and tools.” The three independent components and some of their techniques and tools are listed in Table 2.

Table 2: Three components of TQM (from Hellsten and Klefsjö, 1998 cited in [12])

Values	Tools	Techniques
Top Management Commitment	Control Charts	Quality Function Deployment
Focus on Customer	Ishikawa Diagram	Quality Circles
Focus on Processes	Relation Diagram	Employee Development
Improve Continuously	Factorial Design	Supplier Partnership
Make Decissions on Facts	Process Maps	Benchmarking
Let everybody be Committed	Criteria of MINQA	Process Management
	Tree Diagram	Design of Experiment
	ISO 9000	Selfassessment
		Policy Deployment

In their definition the components are interdependent in such a way that for example Values cannot be established without suitable Techniques. Thus, some listed tools in Table 2 provide the basis for the value of making decisions on facts. Hellsten and Klefjö [16] emphasize the point that TQM should be regarded as a system that evolves, which includes changing values or newly generated ones. They conclude that the role of TQM’s three components –Values, Tools and Techniques– is to increase internal and external customer satisfaction with a reduced amount of resources. More precisely they suggest “[…] to establish a culture based on core values. [16]. This is in line with Bounds et al. [15] who recommend to achieve cultural change through the implementation of values which are chosen in strategic planning session.

A different aspect regarding TQM components is elaborated by Fotopoulos and Psomas [20]. They derived from examining literature around the topic on TQM that it is not clear which of the components comprise TQM and how it is implemented. Having this in mind they propose to organize TQM components in soft and hard elements in order to investigate their impact on quality management results. The categorization of soft and hard elements and TQM results is depicted in Table 3. Rahman and Bullock [21] demonstrated that soft TQM elements have positive contributions on performance indicators and support the idea to define and implement TQM in such a way.

Table 3: Soft and hard TQM elements and TQM results.

Soft TQM Elements	Hard TQM Elements (Quality Tools and Techniques)	TQM Results
Leadership	Cause and Effect Diagram	Customer Satisfaction
Strategic Quality Planning	Scatter Diagram	Employee Satisfaction
Employee Management and Involvement	Affinity Diagram	Impact on Society
Supplier Management	Relations Diagram	Business Results
Customer Focus	Force-Field Analysis	
Process Management	Run Chart	
Continuous Improvement	Control Charts	
Information and Analysis	Quality Function Deployment	
Knowledge and Education	Failure Mode and Effect Analysis	

The examples given under values of Hellsten and Klefjö [16] in Table 2 are largely congruent with the soft TQM elements gathered by Fotopoulos and Psomas [20] and depicted in Table 3. In some cases the terminology matches and in others it varies but does describe the same meaning. While continuous improvement, process management and customer focus match information and analysis might be denominated by make decision on facts. On the other hand Fotopoulos and Psomas [20] list supplier management as a soft TQM element and Hellsten and Klefjö [16] as a technique. Moreover, Fotopoulos and Psomas [20] do not further provide details on quality tools and techniques and leaves the reader with only a fraction of what quality tools and techniques incorporate. As those hard TQM elements they list in Table 3 cause and effect diagram, scatter diagram, affinity diagram, relations diagram force-field analysis, run chart, control charts and quality function deployment and failure mode and effect analysis.

As portrayed there is no rigid definition for TQM. Interpretation and the level of implementation vary across companies. It is an open concept that is applied in different dimensions. This makes TQM a vivid philosophy whose evolvement process is still ongoing. Therefore it is accessible to receive new elements.

2.2.1 Quality Tools

In literature the tools of TQM have evolved, however, the seven quality control tools, firstly selected by Ishikawa [22], are still generally accepted. After Ishikawa's seven tools a new set of seven management tools was presented, which are more related to process mapping and problem solving [23]. Ishikawa's [22] seven basic tools are listed as 'The seven basic quality control tools' and the new set of tools as 'the seven management tools in Table 4.

Many of the basic tools today were developed by a handful of people – Shewart [24], Deming [25], Juran and Gryna [26], Ishikawa [27], Ōno [28], Shingō [29] and Taguchi [30] – starting in the late 1930s. What evolved since that time is the ability for using the tools together programmatically to achieve company-wide benefits [31].

As the "old" TQM tools were more focused on shop-floor visual quality assessment and control the "new" TQM tools are more focused on off-line quality monitoring, action planning and complex problem depicting. Besides those rather direct production management tools the TQM philosophy inspired the development of more sophisticated approaches dedicated to main cause searching, intricate correlations finding, variability controlling and multi-attribute process optimization.

The most widely used tools and techniques are summarized by Dale and McQuarter [32] and depicted in Table 4. McQuarter et al. [33] distinguish a tool as a gadget with a defined function, from a technique, whose range of use is broader and can be composed of different tools.

Table 4: Quality tools and techniques used in industry (suggested by [32])

The seven basic quality control tools	The seven management tools	Other tools	Techniques
Cause and effect diagram	Affinity diagram	Brainstorming	Benchmarking
Check sheet	Arrow diagram	Control plan	Department purpose analysis
Control chart	Matrix diagram	Flow chart	Design of experiments
Graphs	Matrix data analysis method	Force field analysis	Fault tree analysis
Histogram	Process decission program chart	Questionnaire	FMEA
Pareto diagram	Relations diagram	Sampling	Poka yoke
Scatter diagram	Systematic diagram		Problem solving methodology
			Quality costing
			Quality function deployment
			Quality improvement teams
			Statistical process control

According to Ishikawa [17] 95% of the companies' problems can be solved by using the seven basic quality control tools. Critical factors for successful management of quality were studied on the practice dimension and top management's commitment together with a clear vision and strategy emerged as important factors [34]. Top management's commitment together with a clear vision and strategy are important factors. Furthermore, goal setting and deployment as well as a proper planning are crucial. Fotopoulos and Psomas [20] findings after surveying ISO 9000 certified Greek companies indicate that implementing soft TQM elements have a greater impact on quality improvement and the firm's market position than quality tools and techniques. However, they also recommend establishing a TQM culture to support the successful application of TQM elements. Ahmed and Hassan [35] conclude that quality management is supported by the use of suitable tools. Moreover, they identify that a greater implementation of quality management tools results in a better firm performance than a lower implementation.

Quality tools and techniques, as portrayed in Table 4, are described to be practical methods, skills, means or mechanisms used for a specific circumstance [33]. They offer a variety of methods to visualize and control process data and statistics can be applied to gain certainty about cause effect relations [33]. Their purpose when applied is to achieve positive change and improvement [33] and [36]. These tools are remedies to numerous quality problems but might not always take effect. Nowadays information storage and processing capabilities exist but suitable tools are not always available or must be tailored for answering specific questions of interest. If suitable tools are not available knowledge remains hidden in databases [38]. Consequently, novel tools can be devised for quality improvement and assist on the quest for quality improvement. Continuous improvement involves root cause identification and the right selection of the most relevant improvement projects.

Therefore, there are two scopes, which can extend or complement respectively the list of tools and techniques presented in Table 4. During the analysis of the as-is situation the need was identified to device tools for solving specific problems. One tool allows the identification of possible root causes at manufacturing process steps. The other tool presents a prioritization approach among competing alternatives. This tool generation process entails efforts for data analysis, visualization and interpretation.

2.2.1.1 Pattern Identification Through Knowledge Discovery in Databases

One scope to develop a tool is Knowledge Discovery in Databases (KDD) for example, which offers a general framework to generate knowledge from a dataset. KDD can be described as the complete process of discovering useful knowledge from data [37]. Fayyad et al. [37] state that the part of identifying patterns that is relevant for further analysis is a core element. It is referred to as data mining, which is a specific procedure of KDD [38]. Harding et al. [39] define data mining as a concept and algorithm mix consisting of machine learning, statistics, artificial intelligence and data management. But terminology is ambiguous and one must be aware that different communities hold different terms with same meanings. Fayyad et al. [37] compiled across communities the following names for data mining, which is the term used in this thesis: knowledge extraction, information discovery, information harvesting, data archeology, and data pattern processing.

Figure 7 portrays the process of KDD that is described by Fayyad et al. [37] and starts by selecting the relevant target dataset from a database. Preprocessing the target data is relevant to remove noise and outliers for the data to be ready for further processing. On the cleaned data the thoroughly identified or developed data mining algorithm can be performed to generate patterns. The produced patterns must be interpreted and evaluated for the knowledge to be discovered.

Fayyad et al. [37] mention that the data mining algorithm can be composed of a specific mix of the model (the function of the model and the representation form), the preference criterion (some form of goodness-of-fit function of the model to the data) and the search algorithm (the specification of an algorithm for the path of finding).

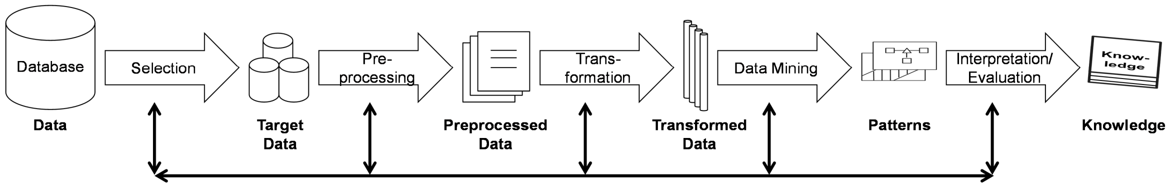


Figure 7: The KDD process c.f. Fayyad et al. [37].

Recent reviews on KDD and data mining for manufacturing exist and indicate the popular use of KDD ([38] – [40]). Some reviews also deal with KDD and data mining surrounding the topic of quality improvement such as predictive maintenance, fault detection, quality assurance, product/process quality description, predicting quality, classification of quality, and parameter optimization [40].

Köksal et al. [40] reported an increasing use of data mining applications for quality related tasks. In those tasks applications for predicting quality are the most widely used ones followed by classification of quality and parameter optimization. There are plenty applications or algorithms respectively to perform data mining. Some of them are maps for classification, regression or clustering of data. Others are summaries, dependency modeling of variables and sequence analysis [37]. Model representation reach from decision trees over linear and non-linear models to case-based reasoning and probabilistic graphical dependencies.

In this sense KDD can provide with a framework to generate knowledge from databases for quality improvement projects. Its core element, the data mining, can be adjusted individually to serve as basis for the generation of a novel quality tool.

2.2.1.2 Prioritization of Improvement Projects

Besides the richness and completeness of philosophies and manufacturing management strategies the selection of the project to develop or the next problem to solve is not always a defined and structured process. Kumar et al. [41] identified room of improvement when selecting the right project within the Six Sigma initiative. Difficulties are independent of the company's performance or level of good administration. Hu et al. [42] assumed that decisions are based on experience and subjective preferences of individual decision makers and that the significance of quantitative support in project selection increases with the number of available projects. Consequently the need for maintaining a tool that assists in prioritizing mutually exclusive alternatives as selection is demonstrated.

Table 5 was built-up to summarize methods and styles of presenting results around selecting improvement projects or selecting lean tools respectively in literature. The Analytic Hierarchy Process (AHP) or variations of it are used and results are presented as ranking of alternatives [43], [41], [44] and [45]. Van de Water and Vries [43] presented in an overview of technical papers of AHP modeling around quality management. The input, however, is mostly qualitative data retrieved from experts. A fuzzy AHP method is proposed by Bilgen and Sen [46] whose objective is to identify the best alternative given their defined criteria. Hu et al. [42] proposed a matrix of alternatives based on a multi-objective mathematical model based on lean and six sigma concepts. They demonstrate that their decision support system can be used in the context of Lean and Six Sigma concept implementation. ANP, also developed by [47] and [48], is rather a network presentation of nonlinear relationships between elements [49].

Table 5: Methods and presenting style in selecting quality improvement projects.

Selection Method	Presenting style of results	Criteria	Project	Author
Analytical Hierarchy Process (AHP)	Ranking of alternatives	organizational fit; customer satisfaction, employee satisfaction; effort and impact variables	Quality improvement project, TQM project selection	van de Water & Vries [43]; Kumar et al. [41]; Ahire & Rana [44]
Multi-objective mathematical model	Matrix presentation of alternatives	Costs and estimated benefits	Implementing lean and six sigma concepts	Hu et al. [42]
Fuzzy Analytical Hierarchy Process (AHP)	Result referral of AHP to select a project alternative	Cost and time of resources; benefits in cost savings, productivity and scrap decrease; effects on quality capacity and energy	Six Sigma project selection and method adoption	Bilgen and Sen [46]
Fuzzy-logic based multi-preference, multi-criteria AHP	Ranking of alternatives		Lean tool selection	Singh et al. [45]
Fuzzy analytical network process (ANP) to prioritize Six Sigma projects	Ranking of alternatives	Strategy, Financial, Customer and Process Improvement	Six Sigma project selection	Boran et al. [48]
Combined analytic network process (ANP) and Decision Making Trial and Evaluation Laboratory (DEMATEL) approach	Ranking of alternatives	Strategies and factors: Risk, cost, benefit, opportunities	Six Sigma project selection	Büyüközkan & Öztürkcan [49]

All methods presented in Table 5 have cost, benefit, risk or effort related criteria. Some authors also consider the organizational fit, customer and employee satisfaction but none is using quantitative or qualitative production data or quality related (real or production derived) data.

2.2.2 Quality Costing

As mentioned when presenting the evolution of total quality in Figure 5 the consideration of cost for improvement activities gained attention. Quality costing is now considered as an important discipline listed as one item of the most widely used tools and techniques (Table

4). However, there is a lack of a clear definition of quality related costs, which can be even found in publications of the American Society of Quality (ASQC) and the British Standards Institution (BSI) [50].

The idea of quality costing firstly emerged during the 1950s. It was Juran [51] who identified the need to estimate the costs of quality and Feigenbaum [18] who presented an approach to categorize them into the areas of Prevention, Appraisal and Failure (PAF).

In literature various terms for quality related costs addressing the same topic can be found. “Quality is free” according to Crosby [14] and costs do only emerge when actions have to be taken when things are not done right the first time. Juran [51] understands costs of poor quality to be the sum of all costs that would disappear if there were no quality problems. However, there are definitions for cost of quality categories for which a generally akin understanding exists.

Moreover, Omurgonulsen [52] reports of cases when terms related to quality costs are interchangeably used. “Quality costs” and “poor quality costs” are used synonymously which basically match with Crosby’s [14] understanding of quality costs to be the price of conformance and non-conformance. Conformance gathers any costs that accrue to do things right the first time, which correspond to appraisal and prevention costs in the PAF scheme. Nonconformance on the other hand holds if work is performed, which does not match with customer requirements. This can be regarded as failure costs in the PAF scheme. Work in this scope typically generates costs for activities such as correcting, reworking or scrapping. Although Campanella [53] reports that one of the main statements of the National Conference for Quality (1982) was that the term ‘Cost of Quality’ is inadequately used since quality is rather profitable than costly it is vividly used by authors and the term CoQ seems to be a widely accepted acronym as shown in [54] – [57].

Feigenbaum’s [18] cost categories prevention, appraisal and failure are widely accepted. The basic assumptions of quality costing is that investment in activities for prevention and appraisal will reduce failure cost and even further investments in prevention will decrease appraisal costs [50]. Hence there is the belief of the existence of a quality level that minimizes costs, which can be visualized by means of a CoQ model. This point of view is represented by the American Society for Quality Control [58] and British Standard Institute [59] and generally referred to as the classical model or view. As one can see in Figure 8 the quality cost model has a cost minimum and any further investments for a better quality level will lead to a higher cost level.

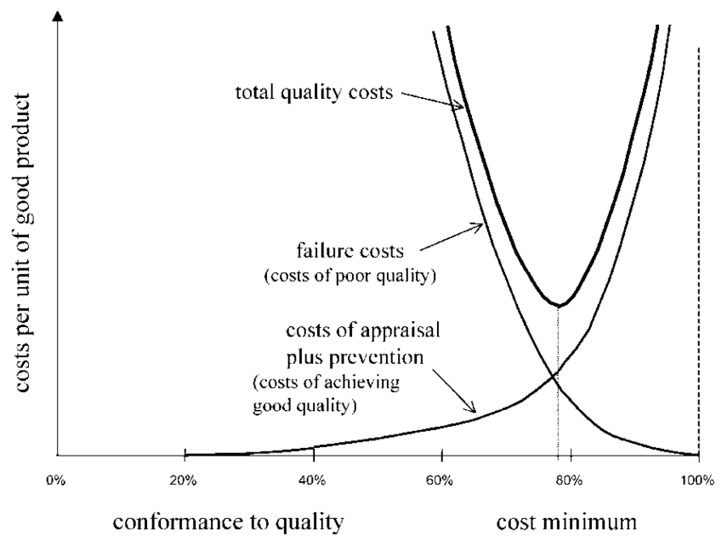


Figure 8: The classical view of CoQ [depicted by [55] from Juran (1951)].

Freiesleben [55] questioned the validity of the classical view due to four reasons: First the model assumes that companies do have a bad quality level and neglects their striving for achieving good quality by means of Six Sigma. Six Sigma for example foresees to minimize nonconforming products occurring on the production line. Second it is a snapshot of the technological status of the company of the time the model is created. Third the model does not take into account learning effects from past improvement activities. And fourth the exponential shape of the unit cost of products of conformance is doubtful since at a higher quality level a higher number of good products absorb the higher costs for prevention and appraisal activities. Juran and Godfrey [13] claim that the classical view is an insufficient effort to strive for perfect quality at a conformance level of 100%. Furthermore, the consequence on sales due to the lack of the ability to quantify failure costs. These are valid points and if the classical view holds and a cost minimum prior to perfect quality exists there is the need to understand the implications of delivering customers with products of imperfect quality.

The new CoQ model epitomizes better empirical findings from industry [55]. Compared to the old model, the new model, displayed in Figure 9, adopted from Juran and Gryna [60], does not show an exponential increase. The cost minimum appears at 100% conformance level that does not impede failure costs. This supports the zero defect philosophy of Deming [61] who assumes the costs of selling nonconforming products to be tremendously high and a minimum can only be found by having a zero defect policy. Following his argumentation would make any efforts in identifying and modeling quality costs obsolete by only pursuing towards zero defects.

The classical CoQ model is also strongly challenged by Plunkett and Dale [50] who are comparing quality cost models such as notional or those supported by real data. They allocate the models into five categories. Burgess [62] ties up to the five categories and provides a denser categorization into three groups. In his work he provides evidence, by means of modeling the dependencies of quality-cost elements, that validates both views, the modern and the classical one. He goes on and suggests the classical view for a time constrained consideration and the modern one for an infinite time horizon and proclaims that any investment in prevention is always beneficial in the long term.

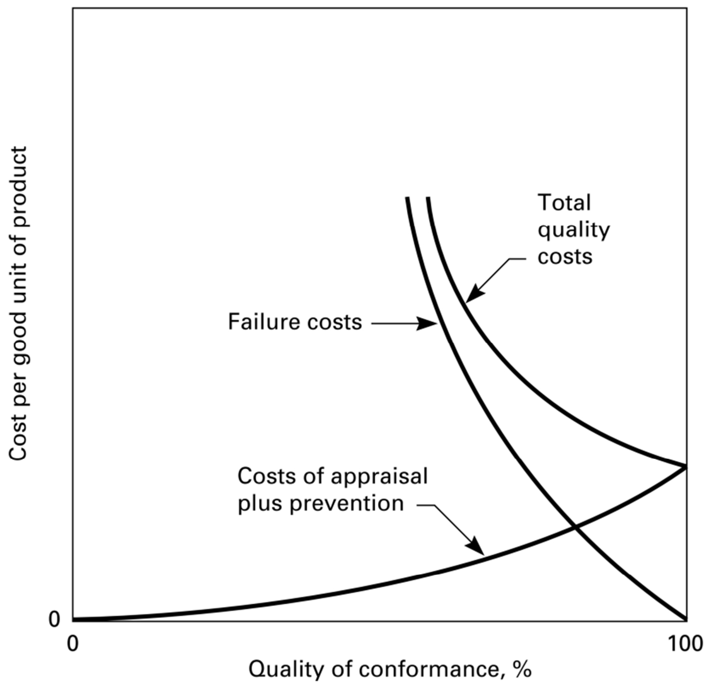


Figure 9: The modern view of CoQ (depicted from [13].

Schiffauerova and Thomson [56] summarize quality cost models in the areas of the PAF model, Crosby's model, opportunity or intangible cost models, process cost models and activity based cost models (ABC). Their findings indicate that all models applied in industry are rewarded with positive effects on cost savings. However, in literature the classical PAF approach is widely spread [50], [56].

Both of the models in the classical and the modern CoQ view can be valid. Applying CoQ models have proven to be financially beneficial by industry. Furthermore, the quantification, or the expression as costs respectively, can support the initiation of improvement projects since it is a great way to establish quality cost awareness. The different approaches to model quality related costs are further detailed in the next sub-sections.

2.2.2.1 Prevention, Appraisal and Failure

Feigenbaum's [18] definition of the PAF cost categories are such as follows: **Prevention costs** are for the purpose of keeping defects from occurring in the first place. Included are costs such as quality control engineering, employee quality training, and the quality maintenance of patterns and tools. **Appraisal costs** include the expenses for maintaining company quality levels by means of formal evaluations of product quality. This involves such cost elements as inspection, test, quality audits, laboratory acceptance examinations, and outside endorsements. **Failure costs** are caused by defective materials and products that do not meet company quality specifications. They include such loss elements as scrap, spoilage, rework, field complaints, etc.

2.2.2.2 Process Cost Modeling

Based on Ross's [63] idea of a process cost model first applications on quality cost systems emerged [56]. The process cost approach for quality costs is regulated by the British Standards [64]. Any process can be modeled taking into account its costs and in that perspective the standards foresee a distinction between cost of conformance (CoC) and Cost of Nonconformance (CoNC). But in contrast with Crosby [14] CoNC specifically refers to the process not operating to the defined standard [65].

Busch [66] developed a method which is named process-based cost modeling (PBCM). Herein, costs derive from part design, material properties, and operating conditions [67], [68]. In the context of quality costs Zaklouta [69] analyses by means of a PBCM the tradeoffs of different inspection strategies in manufacturing.

2.2.2.3 ABC / TDABC

Activity Based Costing (ABC), developed by Cooper and Kaplan [70], can also be used as a CoQ model. It can be used for the identification, quantification and allocation of quality costs

[56]. The mechanism of cost measuring depends on the activities involved for production and delivery of goods and services [70]. Therefore resources are allocated to activities and those activities to products in order to identify the costs [70]. Tsai [71] presents in his work an integrated system of CoQ and ABC, which shares a common database for cost and non-financial information with the objective of identifying opportunities for quality improvement and disposing non-value-added activities.

Kaplan and Anderson [72] present a simpler ABC version - the Time-Driven Activity-Based Costing method. In contrast with ABC, TDABC is easier to establish, maintain and use and delivers more precise results [73]. This is due to the use of time equations, which make exhaustive and time consuming data gathering through interviews obsolete [72] and [73].

2.2.2.4 Simulation and Quality Costs

Cost of Quality models can be used as a monitoring tool but by means of simulation the reporting of historical data becomes a tool that allows predicting and calculating the behavior of a system with various changes [74]. This is a cost effective procedure because these types of experiments do allow taking conclusions prior to investments or rearrangement of system elements. When simulating and taking into account quality costs the focus can either be set on the entire manufacturing system, but only roughly detailed, or on single stations which are very detailed [75].

Jahangirian et al. [76] structure the literature concentrating on simulation in the area of manufacturing and business in three categories: (A) Real Problem-Solving papers – real data is used for problem solving; (B) Hypothetical Problem-Solving papers – the use of artificial data for solving a real life problem; (C) Methodological papers, dealing with the enhancement of simulation itself without application or experiments. Solving real problems and using real data is most popular according to their empirical study. Discrete Event Simulation (DES) is the most used simulation technique, followed by System Dynamics (SD), Hybrid Simulation and Agent Based Simulation (ABS).

Contributions from several authors are available analyzing financial impacts by simulating different quality strategies or manufacturing system behavior. Hereby the approaches in simulation techniques or cost analyses vary as one can see in Table 6. The table categorizes simulation techniques, software used, simulation type, the empirical nature of the paper, the cost criterion and a short description of what was modeled. It presents papers of discrete event based, or continuous simulation dealing with real or hypothetical problem solving.

Discrete event based simulation is used by [77], [78] and [79]. Ruyter et al. [77] analyze the impact of quality control and inspection errors on quality costs for a real problem of an automotive stamping process. Hereby they conclude that inspection errors contribute highly to increasing total quality costs and allowing nonconforming products accumulating before resetting the line is cost effective. Thiagarajan and Zairi [34] also simulate a real problem in which various system designs of control charts are modeled and analyzed on costs by means of the activity based costing approach. Burgess [62] simulates a manufacturing including an inspection and rework cell, which is formulated as a hypothetical problem. Conclusions on quality costs according to the PAF approach and in comparison to an approach of gathering disruption costs are drawn.

Continuous simulation is the type of simulation in [74], [75], [77] and [62]. Burgess [62] models the dependencies of the PAF elements in a hypothetical problem solving approach and identifies the effects of investments in prevention activities on the other cost elements. Tannock [80] provides in his hypothetical problem an analysis on costs of different quality control strategies of a manufacturing process. Visawan and Tannock [75] present a real problem solving simulation from the Thai automotive industry. Hereby they analyze the impact of investments in prevention on manufacturing costs and benefits, which take into account market responses according to quality levels. Clark and Tannock [74] investigate a real case from the automotive industry and the findings highlight the importance of quality costing together with simulation for enhancing decision making.

Gardener et al. [81] propose four inspection and removal strategies and analyze their influences on profitability and productivity. The strategies are inspection and removal of defectives: (1) at completion of finished product only; (2) prior to assembly points; (3) following every operation; (4) based on acceptance sampling prior to assembly points. They describe quality costs as the difference of the as-is situation compared to the to-be situation.

Another way of expressing quality in monetary values rather than in statistical terms is described in [82]. In their analysis of a manufacturing process they consider statistical quality control in order to calculate costs per cycle. An extension of their work can be found in [83] where they analyze the proposed manufacturing process with Gardener's et al. [81]

four strategies regarding inspection and removal to conclude what the implications on costs are.

Table 6: Categorization of literature dealing with simulation and quality costs.

Author(s)	Simulation Software	simulation type				Costing approach	Empirical nature of the paper			Testing object / Modelling
		event-based discrete	domain specific	continuous simulation	mathe-mathical tools		Real Problem-Solving	Hypothetical Problem-Solving	Methodo-logical	
Burgess [62]	ithink			x		PAF		x		The dependencies of the P-A-F elements.
Clark and Tannock [74]	Visual Basic			x		Cost per unit	x			Production process of a real system
Gardner et al. [81]	SLAMSYSTEM with MS FORTRAN 5.1 inserts					Cost reduction (As-is - to-be)		x		Four strategies for inspection and removal of defectives are modeled of profitability.
Ruyter, Cardew-Hall & Hodgson [77]		x				PAF	x			The impact of inspection and control errors on quality costs.
Spedding & Chan [78]		x				Activity-based costing				Simulation of trial and error methods for the implementation of control chart.
Tannock [80]	Visual Baasic			x		Qmp (Appraisal costs + Taguchi q-loss)		x		Different inspection strategies and impacts on costs. Cost reduction after different improvement actions.
Tannock & Saelem [79]	Arena	x				PAF and disruption costs		x		Disruption costs are compared to PAF elemetns.
Visawan & Tannock [75]	ithink			x		PAF + price quality relationship	x			Quality spending levels which result in maximum profit for a Thai automotive manufacturer.

As shown in Table 6 models vary in complexity, simulation technique and costing approaches. Costs are taken into account by analyzing the PAF cost elements or other approaches such as illustrating the comparison of unit cost of different manufacturing or inspection strategies. A very simple calculation of the difference of the as-is and the to-be status has been carried out. One can say that models represent more or less complex the production environment and take into account costs to provide a mean for decision making. But neither does the literature, analyzed in Table 6, indicate advantages of using a specific simulation type or software nor suggests a specific costing approach. One might find reasons for that in the facts that simulation models are custom-designed and industrial environment dependent and quality cost models tailor made. One conclusion one could draw is that any activity in analyzing a systems behavior by simulation and analyzing the corresponding costs will enhance the decision making process prior to real system changes in a cost efficient way.

As mentioned above there is a number of literature available analyzing quality costs and simulation, however, there is no study analyzing the adoption of soft TQM elements on quality costs. In this study the effects on quality costs by the adoption of soft TQM elements is analyzed by means of DES modeled in arena software.

2.3 Inspection Strategies

At an inspection system a part, a module or the finished product is evaluated against requirements, which can be of technical, esthetical or functional nature. Terminology is ambiguous and in literature testing and inspection strategies are used interchangeably. Numerous models can be found where researchers approach the topic on inspection strategies in different ways. Mathematical optimization, simulation or hybrid models can be found among them as one can see in Table 7. The models in Table 7 take into consideration multistage or a final inspection stage. Multistage consist of a series of manufacturing or production processes. Each stage can include a coupled subsequent inspection activity upon the previously performed tasks [84], [85]. Multistage can also include a series of complementing and mutually disjoint or repetitive inspection activities. Hereby, the inspection stations are sequentially allocated with confined inspection tasks at each stage [86], [87]. Models can also include the inspection of multi characteristics at one stage or the inspection of each one of the multi-characteristic spread over several stages [89].

Table 7: Overview of models to minimize inspection cost.

Researcher	Inspection Type		Inspection strategies	Minimizing costs with cost categories	Modeling
	Multistage inspection	Final inpection			
Ding et al. [90]		x	Single inspection, Re-inspect Rejected, Re-inspect Accepted	Inspection and Scrapping cost	mathematical
Van Volsem et al. [84]	x		The number and locations of inspection stations; the number of inspections executed (sampling size & frequency) for each station; the rigor (acceptance limits) of the inspections for each inspection station	Sum of inspection cost + rework / part replacement cost + penalty cos for delivering faulty products to customer	Discrete event simulation and evolutionary algorithm
Vaghefi and Sarhangian [85]	x		The number and locations of inspection stations; inspection parameters (sample size, acceptance number)	test cost, rework / replacement cost, penalty cost	Discrete event simulation and simulation optimization
Korytkowski and Wisniewski [89]	x		The number and locations of inspection stations; the location to perform rework	test cost, rework cost, scrap cost, Failure Type I and failure Type II cost	Discrete event simulation and tabu search algorithm
Raouf et al. [86]	x		The number of inspections	test cost, Failure Type I and failure Type II cost	mathematical
Duffuaa and Najjar [88]	x		The number of repeat inspections and sequene characteristics for inspection	test cost, Failure Type I and failure Type II cost	mathematical

Ding et al. [90] use the term testing strategies to describe different process configurations of repetitive testing at the inspection. This approach can be allocated into the strategy category of inspection-oriented quality assurance. Mandroli et al. [91] distinguish literature on the topic of inspection strategies into the branches inspection-oriented quality assurance and diagnosis-oriented strategies. Inspection-oriented quality assurance focuses on the allocation of inspection activities to minimize total manufacturing costs, which are composed by the cost elements of appraisal and failure. Diagnosis-oriented strategies, also referred to as sensor distribution strategies, use analyzed data of failure detection for process amendments with the goal of product or process improvement to approach the near-zero nonconformance level [91]. Mandroli et al. [91] go on and state that the inspection-oriented strategy may improve the product quality to the customer but does not impact process or product improvements prior to shipment.

An installed inspection system can apply different approaches to test products. Ding et al. [90] describe different inspection strategies such as single inspection, re-inspect rejects and re-inspect accepts, which are further explained hereafter. Their proposition is that the inspection process is imperfect and one must take into account probabilities for the correctness of inspection decisions. As a result one can define different favorable inspection strategies in terms of costs for different combinations of quality levels and detection probabilities. This becomes quantifiable with quality related costs as presented in 2.2.1.

Ding et al. [90] describe three generic inspection strategies: *single inspection*, *re-inspect rejects* and *re-inspect accepts* which are portrayed and described in the following:

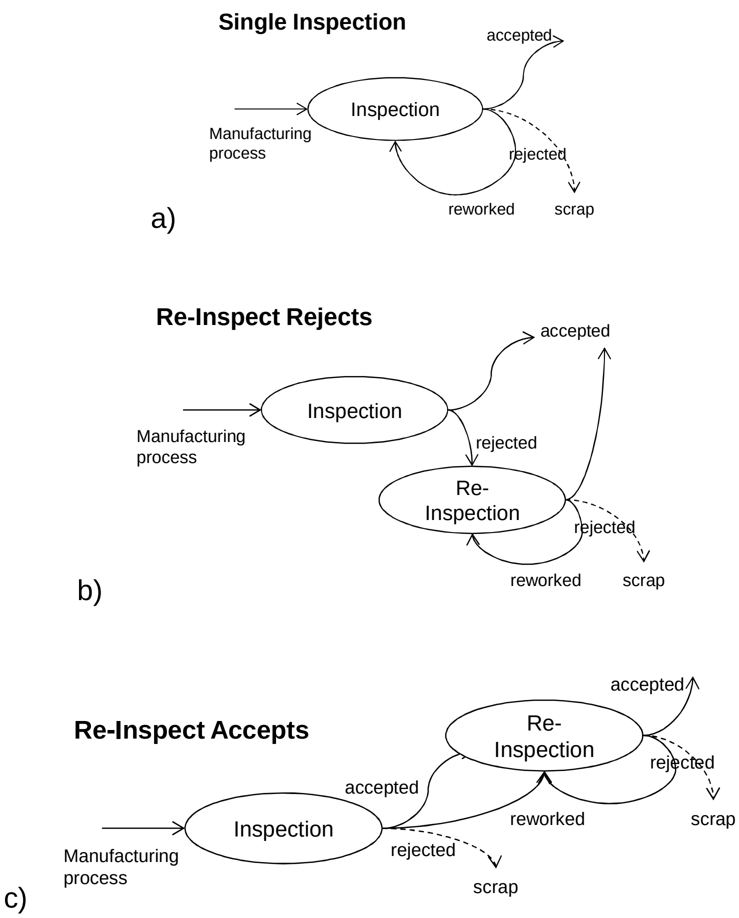


Figure 10: Flow diagram of generic inspection strategies. a) Single inspection, b) re-inspect rejects, c) re-inspect accepts.

All products are inspected after the manufacturing process upon conformance. At the *single inspection* strategy, illustrated in Figure 10 a), conforming products are accepted and forwarded to be shipped for delivery and nonconforming items rejected. Depending on the recoverability of rejected products they are either sent to be reworked or scrapped. Reworked items are inspected and subject to a new appraisal decision as described before.

The *re-inspect rejects* strategy also foresees all the products to be inspected at the end of the manufacturing process, as presented in Figure 10 b). Conforming products are sent to the customer and nonconforming products are rejected. Rejected items are re-inspected at a second inspection station to ensure the correctness of the previous inspection decision. At this stage conforming products are forwarded to the customer and nonconforming products rejected. Depending on the recoverability of the product it is sent to be reworked or scrapped. All reworked items are re-inspected again and subject to a new appraisal decision.

All products are inspected after the manufacturing process at the *re-inspect accepts* strategy as depicted in Figure 10 c). In contrast with the other strategies conforming products are re-inspected to ensure the correctness of the first inspection decision. Re-inspected conforming products are sent to the customer and nonconforming products are rejected. Rejected products of the inspection and the re-inspection stage are depending of the recoverability of the product sent to be reworked or scrapped. Reworked items are re-inspected and subject to a new appraisal decision.

In summary one can say that the single inspection strategy signifies the least handling of all strategies and therefore should imply lowest process costs. However, depending on the correctness of the decision, declared conforming products might be in fact nonconforming and be sent to the customer. Likewise as nonconforming declared products might in fact be conforming and either generate inefficiencies through additional inspection or be unnecessarily scraped. Thus, when adopting the re-inspect reject strategy one aims to mitigate unnecessarily scrapping or reworking products. The re-inspect accepts strategy diminishes the risk of sending nonconforming products to customers.

Zaklouta [69] builds on the inspection strategies of Ding et al. [90] and examines through probabilistic cost of quality models fundamental inspection strategies. The three strategies are presented with probabilities for testing errors and mathematically formulated [69].

Figure 11 illustrates in a 2x2 matrix the combinations of inspection results [69]. The true quality state of the product is characterized horizontally and is either conforming (C) or nonconforming (NC). The appraisal decision is characterized vertically and the inspector makes a decision upon the product to be conforming (DC) or nonconforming (DC). The combinations of decisions and true quality states result in four possible outcomes. Of those outcomes two can be correct and two incorrect results are depicted in Figure 11. For a conforming product the decision can be incorrect with the probability α and correct with the probability $1 - \alpha$. For nonconforming products the decision can be incorrect with the probability β and correct with the probability $1 - \beta$. Conforming product routs are indicated with a solid line nonconforming routs with a dashed line.

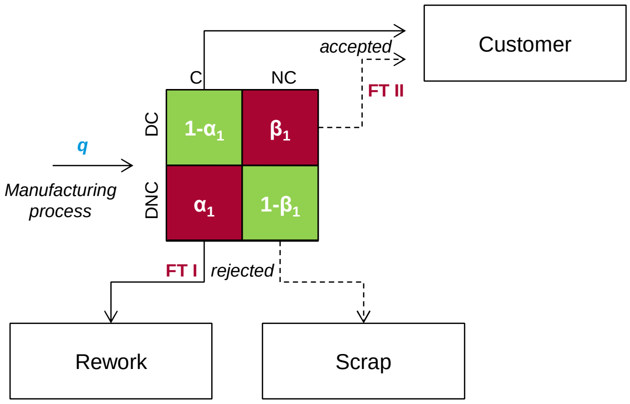


Figure 11: Flow diagram of single inspection strategy with correctness of inspection outcome.

Literature denotes incorrect decisions with failure type I and failure type II. Rejecting conforming products is failure type I (FT I). Accepting nonconforming products is failure type II (FT II). FT I causes inefficiencies through unnecessary handling, such as rework or repetitive inspection and is by far less problematic than FT II. The latter means the delivery of nonconforming products to customers.

Figure 12 presents the flow diagram of the strategy *re-inspect rejects* together with the correctness of inspection outcomes. The strategy presents a two stage inspection. The first stage is identical to the single inspection strategy with the only difference of the subsequent treatment of rejected items. All rejected items are re-inspected and the combination of inspection outcomes, as presented before, applies again. Thus, the same portion of products, conforming and nonconforming, is sent to the customer at the first inspection stage as in the case of the single inspection strategy. In addition to that, the number of rejected products at the first inspection stage that receive a conforming decision at the re-inspection stage is also sent to the customer. Rejected products are re-evaluated upon conformance. Depending on the correctness of the re-inspection, re-inspected conforming products can be saved from being scrapped or unnecessary rework. Reworked products are re-inspected at the re-inspection station.

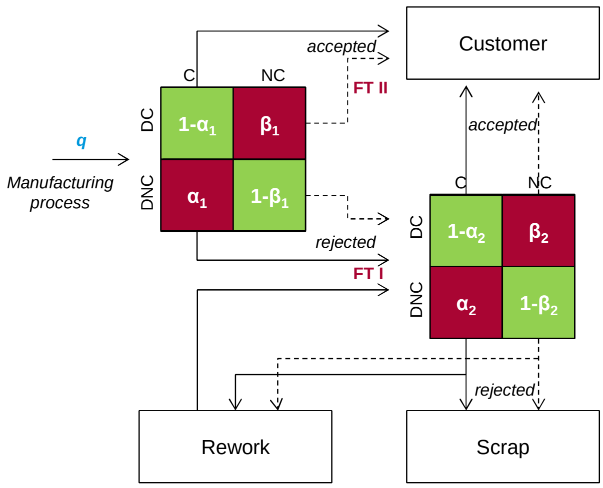


Figure 12: Flow diagram of re-inspect reject strategy with correctness of inspection outcome.

Figure 13 shows the logic of the *re-inspect accepts* strategy. Accepted products at the first inspection stage are re-inspected at a second inspection stage. Only if the second appraisal decision is positive the product is sent to the customer. At each of the two inspection stages rejected products are depending on the recoverability sent to rework or are scrapped. After rework the products are re-inspected at the second inspection stage.

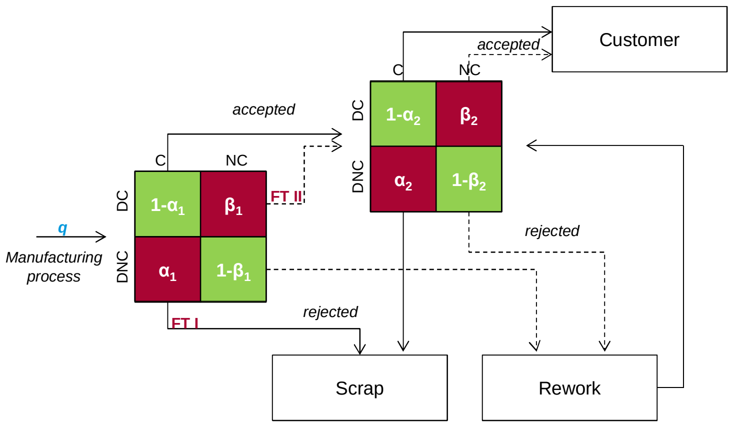


Figure 13: Probabilistic view of the re-inspect accepts strategy.

Zaklouta [69] implements a CoQ framework, which expresses Feigenbaum's [18] cost categories according to the general inspection strategies in [90]. This framework derives from a probabilistic view an expected value approach and a notation of costs is established, which is presented in (1) – (7):

Zaklouta [69] describes the cost beyond perfect manufacturing [CBPM] to be the sum of the Feigenbaum's [18] cost categories but reduced by the prevention cost element of producing conforming products (n_{co}).

$$CBPM(n_{co}) = C_{appraisal}(n_{co}) + C_{internal\,failure}(n_{co}) + C_{external\,failure}(n_{co}) \tag{1}$$

Moreover, the costs of imperfect manufacturing and inspection are the sum of CBPM and the cost of perfect manufacturing (CPM). CPM is the manufacturing costs per item c_p multiplied with the quantity of delivered conforming products.

$$CIMI(n_{co}) = CPM(n_{co}) + CBPM(n_{co}) \tag{2}$$

With

$$CPM(n_{co}) = c_p * n_{co} \tag{3}$$

Cost of nonconformance is expressed by scrap cost, which is the material cost c_m and manufacturing process cost c_p. Delivered nonconforming products are subject of a penalization cost c_f.

$$c_s = c_p + c_m \tag{4}$$

And

$$c_{nco} = c_p + c_m + c_f \tag{5}$$

Equation (1) is proposed to be expressed as follows [69]:

$$CBPM(n_{co}) = (n_s * c_s) + (n_{nco} * c_{nco}) + \sum_i \sum_j n_{I_{i,j}} * c_{I_i} + \sum_{k=1}^{l} n_{R_k} * c_R \tag{6}$$

With i Zaklouta [69] denotes the inspection method and j the number of inspection cycles of the number of items $n_{I_{i,j}}$ being inspected.

Deriving from the above presented equations (1) to (6) Zaklouta [69] analyses analytically, by means of a discrete event simulation and complements the inspection strategy analysis with a utility analysis. In the analytical model $n_s, n_{nco}, n_{I_{i,j}}$ and $n_{R_{i,j}}$ are treated as random variables. These are an approximation to an expected value, which is presented for each inspection strategy in a probabilistic approach.

$$\begin{aligned} E\left[cimi_{co,Single}\right] &= c_p + \left(\beta^{l+1} + \alpha * \sum_{j=1}^{l+1} \beta^{j-1}\right) \\ &* \left(c_p + c_M\right) + \alpha * \sum_{j=1}^{l+1} \beta^{j-1} * c_f \\ &+ \sum_{j=1}^{l+1} \beta^{j-1} * c_{T_{1,f}} + \sum_{k=1}^{l} \beta^k * c_R \end{aligned} \tag{7}$$

An example of this approach, the *single inspection* strategy, is presented in (7).

The established metric to formulate inspection outcomes according to inspection strategies is a good approach to estimate quality costs. The formulation allows the consideration of the fallibility of inspection systems in order to quantify the possible damage of imperfect inspection systems. Furthermore, with scenario analysis this framework can contribute to understand the effect of how mitigation of the fallibility can be expressed in cost reduction.

2.4 Progress Functions

Progress functions are similar to learning curves. Literature around the topic of learning curves is extensive. It was firstly Wright [92] who identified the need to understand the variation that occurs of “the effect of quantity production on cost”. His model, formulated as a power function (8), is described to be the log-linear model and by far the most adopted one [93]. A learning curve can be described as the effect of decreasing unit costs at an increased cumulative production volume. In the log-linear model the labor hours to produce a unit decrease by a factor when doubling the production volume. While the log-linear learning model is predominantly used it does not implicitly describe the best fit of experience to companies [93].

The learning rate can be understood as what percentage of the original input remains after doubling the production volume.

$$h_V = a * V^{-b} \tag{8}$$

The learning curve can be mathematically described as in (8) where h_V is the number of labor hours to produce the V_{th} unit. V is the cumulative production volume of the observed period. The parameter a is the number of hours required for the first unit. Thus one can state $a = h_1$ for the first unit of production. The learning index is described as b [93]. It is directly related to the progress ratio p as stated in (9). The learning index b is also referred to as learning curve exponent [96], rate of reduction [95] or progress rate [94]. Besides the term progress ratio to describe the variable p, as Argote and Epple [95] do, also the term learning rate is used [93] and [96].

$$b = \frac{log(p)}{log(2)} \quad \leftrightarrow \quad p = 2^{-b} \tag{9}$$

With the relation of progress ratio and learning index in equation (9) an example can be given for better interpretation [95]: A progress ratio of 80% (equivalent to a learning index of 0.322) implies that for each doubling of cumulative output a 20% cost reduction in unit cost is achieved.

In literature similar effects hold different terms such as learning curves, progress functions or experience curves [94] and [95]. Furthermore, learning rates are distinguished from progress rates in terms of on what level and where the effect takes place. The learning phenomena of learning curves, focuses on an individual employee level or production process. Progress functions might also take into account differences in materials inputs, process or product technologies, or even managerial technologies and effects from a process to firm level [94]. Dutton and Thomas [94] point out that progress functions can be a collective effect, which might not stem only from knowledge increase but also from current revision of habits, increased production output generated through production method or process improvement. Progress functions do vary not only across industries and firms but also within firms over time ([97] [94] and [98]). Experience curves generally refer to progress at an industry level but could occasionally comprise firm level as well [94]. The differences according to Dutton and Thomas [94] are listed in Table 8.

Table 8: Classification of different types of the learning phenomena [94].

Term	Definition
Learning curves	▪ Labor learning at level of individual employee or production process, such as assembly line
Progress function	▪ Also changes in materials input, process or product technology or material technology from level of process to level of firm ▪ Also improvements of increased knowledge ▪ Revised production methods ▪ Progress is used to describe a result of firms gaining knowledge
Experience curves	▪ Level of firm or progress at an industry level ▪ Also used as a proxy to capture progress effects ▪ Experience is used to describe means for firms getting knowledge

Argote and Epple [95] describe the effect of organizational learning. Organizational learning curves consider the learning effect of a whole organization or an organizational subunit (for example, manufacturing plants). Additional factors can be included such as technological developments and improved coordination of the production process [95]. Thus, organizational learning involves more than individuals becoming better at their particular jobs.

Other models of learning are thoroughly investigated in terms of models, applications, industries, and parameters. Besides the log-linear model Yelle [93] refers to the plateau model, the Stanford-B model, the DeJong model and the S-Model. Badiru [96] concludes that the use of multivariate models of learning curves provide a detailed cost and productivity analysis for economic and production processes.

Testing different learning indices to understand the implications of the impact range is advantageous compared to adopting progress rates from historical data or relying on one stable progress rate. The prediction of future progress rates from past improvements is not reliable enough [94]. Moreover, unexpected variability can contribute to wrong estimates in predicted costs.

Dutton and Thomas (1982) (cited in [94]) identify four causal main categories by which progress is caused: (1) effects of technological change; (2) Horndal (labor learning) effect; (3) local industry and firm characteristics; and (4) scale effects.

(1) Improving capital goods creates an environment that endorses progress effects which Arrow [99] describes by the “learning-by-doing” notion. This notion is empirically supported by Sheshinski [100] who also identified that cumulative investment is favorable compared to cumulative output in terms of experience.
(2) The Horndal-plant effect originates from direct or indirect labor learning referring to a type of capital goods (Lundberg, 1961 in [94]). Dutton and Thomas [94] mention that this effect can be linked to or occurs in interaction with economies of scales. Hereby literature around the Horndal-plant effect considers direct labor learning due to performance improvement of fixed tasks [94]. Another contributor to the Horndal effect that affects direct-labor input is indirect-labor behavior learning. Plateauing effects on the direct-labor input is observable if no further tooling or process changes are made. Cases with machine-intensive processes show rather minor progress of direct labor and the main factor is attributable to indirect-labor learning, technical adaptation by personnel on employment or administer level [101]. Dutton and Thomas [94] summarize that although there is empirical evidence for the Horndal effect the exact relationship between causes and progress effects is not fully understood. Among the causes for progress they list tooling, process design changes among others.
(3) Dutton and Thomas [94] outline the variable nature of the learning index. Influential elements of the progress curve are differences of operating system characteristics such as the type of implemented production processes, automation and performance characteristics. However, the exact relation of system characteristics and the progress curve is not fully understood [94].
(4) Economies of scale, cost reduction with increased scale are numerously attributable. Scale and non-scale effects are both considered as interacting effects and the progress function does not distinguish between the two formerly mentioned [94].

In literature there is furthermore the source of progress and its occurrence discussed. The approach of Levy [102] to distinguish the origin of progress into exogenous and endogenous sources and its occurrence onto induced and autonomous learning is widely accepted.

As portrayed in this chapter modern manufacturing systems consider TQM elements. TQM is an open field that welcomes new elements to contribute to its incomplete evolutionary process. Tools and techniques of all TQM elements must be tailored if they are not readily available. This brings KDD to the front. The methodology to discover knowledge from a dataset can be used as a quality tool with for the purpose appropriately designed data mining algorithms. Moreover, TQM foresees the selection of the right improvement projects. In order to making the right choice prioritization is inevitable. But improvement is more impactful when expressed in costs. Thus, a proper procedure to determine quality related costs is necessary. There is room for improvement if a state of perfect quality is not yet reached. And since a quality level prior to perfect quality can be beneficial, there is the need to capture costs beyond perfect quality. A method that assesses cost effects of imperfect quality is required to determine a favorable inspection strategy. But this method must also take into account learning effects by the implementation of quality improvement initiatives.

CHAPTER 3

3 Problem Statement and Tools Development for Analysis

This section describes the as-is situation of the affiliated company's reality. The chapter is divided in three sub-sections.

Section 3.1 describes the manufacturing process of the affiliated company. Furthermore, it expresses retrieved and treated data of the company's information system with graphical illustrations for better understanding. A process map of the plant's production processes is presented together with a detailed process flow diagram of the product inspection. Complementing to the description there is a quantitative and qualitative assessment done upon manufacturing process data.

Section 3.2 deals about the nonconformities of the products. After presenting the types of NCs two methods are developed to better study the situation. Novel tools were devised to analyze possible root causes of nonconformities and to prioritize the most important ones.

Section 3.3 presents a simulation model of the real system. The results of the analysis provide with advices for improving the manufacturing process of the inspection processes.

3.1 Qualitative and Quantitative Assessment of the Performance

The company is a producer of a high technology automotive part. The product is important to the driving performance characteristics and safety. The company maintains a quality management system and is certified by quality standards such as DIN EN ISO 9000, DIN EN ISO 9004 and ISO/TS 16949.

It is necessary to dominate well various scientific fields to manufacture the product, which runs through different basic processes. Mixing of raw materials, assembling subassemblies and an injection akin process characterize the production steps. Each step consists of numerous machines and every product passes exactly one machine at every step. Barcodes are attached to the product and every machine equipped with a barcode scanner records the product machine relationship to a database. Thus, the database offers information about the history of the product path through the production steps and through the individual machines.

The spectrum of processes in each step range from fully automated, to fully manual up to semi-automated processes. The company produces a high technology and complex product which varies in size and composition. The product is produced in a large production volume and production related data is massively available. An inspection station located at the end of the manufacturing line appraises the final product upon conformance to requirements prior to shipping. The product inspection is entirely humanly based and performed on 100% of the production volume. Conforming products are forwarded to be shipped to the customer. Nonconforming products are evaluated. The type of NC is added to the information system and a decision of the recoverability through rework or the product to be scrapped is taken. The causes of nonconformities are manifold and attributable to a number of reasons due to the complex nature of the product and of the processes. Among those are process failures, machine stoppages, incorrect raw material composition, inferior quality of raw materials and human error. In addition NCs are often only detectable at the finished product. They vary from minor cosmetic to severe imperfections that may not be recoverable.

During an internship of six months in the form of a full time placement at the company the data presented in this thesis was gathered. Data was retrieved from the information system, collected through observations and interviews conducted.

3.1.1 Process Mapping

In this section the entire manufacturing process of the plant is presented. The first map (Figure 14) depicts all processes to provide a holistic view of the manufacturing plant. In a second step the inspection process is depicted in detail (Figure 15). The map contributes to understand the complexity of the manufacturing process, which can be sources of variability.

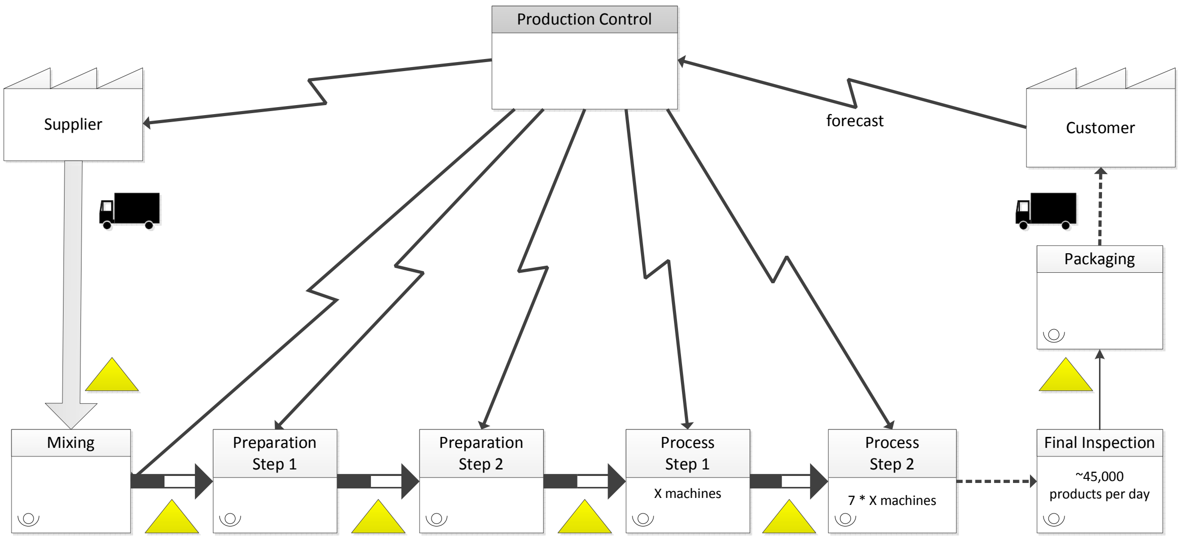


Figure 14: Production processes of the company under analysis.

The first step in Figure 14 is the mixing of raw materials. Several numbers of different raw materials are added under exact weights, depending on the particular recipe of the individual product's components. After the mixing of raw materials there are two preparation subsequent steps. Among the machines of preparation extrusion and calendar based processes are executed. All intermediate products are delivered to process step 1 where the product is assembled. Depending on the type of product and brand the final item is composed of different sub-assemblies. Thus, the product can vary in geometrical dimensions, raw material composition and reinforcement of parts of the product. This results in variations of a product with different performance characteristics. Process step 2 is an injection akin process where the product receives its final characteristics such as shape among others. All process steps until the final inspection follows the principle of push. This means that based on forecasts the products are manufactured. After the single manufacturing steps the intermediate products are gathered in intermediate storage systems. At the final inspection station a pull triggered system is installed. Operators at the inspection system demand the products from a buffer system.

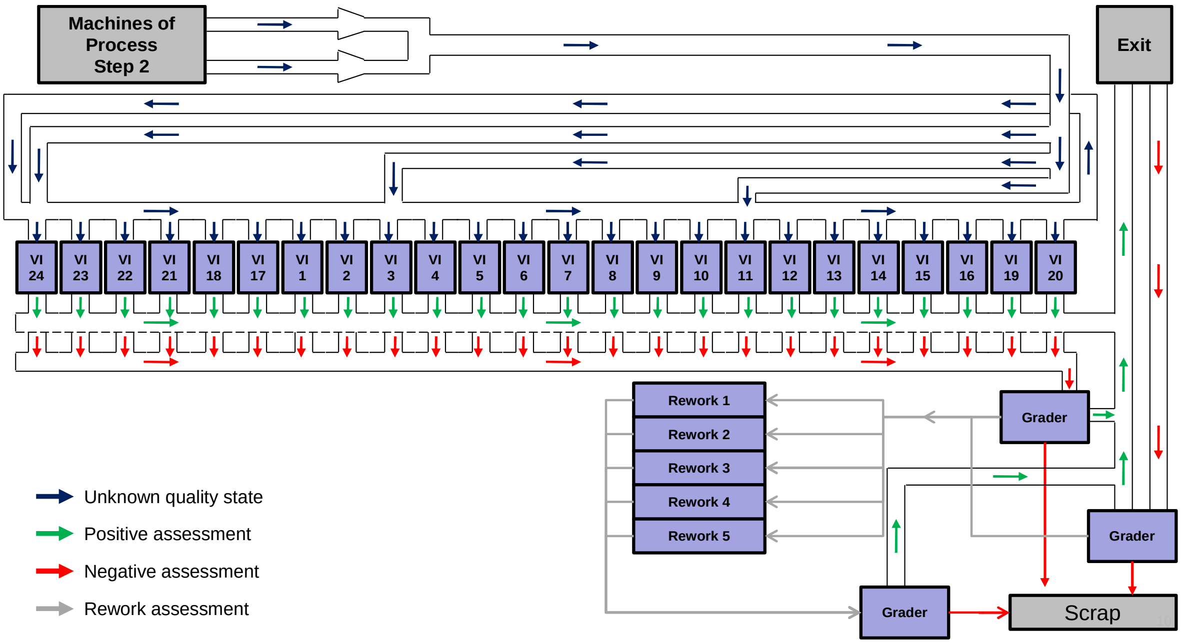


Figure 15: Detailed process flow diagram of final inspection process step.

Figure 15 depicts a detailed version of the process flow diagram of the final inspection process step – the inspection system. All products which leave the machines at process step 2 merge into a conveyor system. This conveyor diverges and feeds three attached conveyers with products. After the division the three conveyors end in a conveyor circulation system around the final visual inspection station (VI). The entrance into the conveyor circulation system is arranged in such a way that the distance to the inspection stations is equal. The first conveyor end feeds the first eight inspection stations, the second conveyor end the second eight inspection stations and the third conveyor end the third eight inspection stations. Each inspection station is equipped with a small buffer. If the buffer limit is reached further products are rejected to enter that particular station and forwarded to the next station. Access is granted when the number of products in buffer is reduced. In case all individual buffers of the inspection stations have reached its limit the products continue in the circular conveyor circulation system until a spot in the individual buffer of an inspection station is available. The circular buffer system is also limited and once the limit is reached access to it from the three feeding conveyors is denied and products keep accumulating. If not solved in time the accumulation can reach such an extent that the machines of production step 2 are blocked and cannot process products anymore and remain idle.

The blue arrows represent the product flow of products of unknown quality state. Green arrows represent a product flow of products assessed as conforming. Red arrows represent the product flow of products evaluated as nonconforming.

Each visual inspection station in Figure 15 can be operated by a human operator – a visual inspector. The visual inspector inspects the products upon conformance to requirements. Conforming products are accepted and forwarded and exit the inspection process. Nonconforming products are rejected and forwarded to a grading station, which re-inspects the product. Three possible outcomes of this assessment can be achieved:

1. The product could have been rejected incorrectly and after the re-inspection assessed to be conforming. In that case the product is released and forwarded.
2. The re-inspection result is affirmative, so the nonconforming type, the nonconformity, is assessed. Nonconformities (NCs) vary from minor cosmetically imperfections to severe safety related imperfections. Depending on the type or the degree of the NC it is recoverable through rework or a combination of different types of rework activities.
3. Non recoverable products are scrapped.

All reworked products are reassessed by a re-inspection station (referred to as grader in Figure 15) similar to the one previously described including its assessments.

3.1.2 Average Daily Production Volume

The operating processes of the plant are designed to target a yearly production volume of around 15,000,000 to 16,000,000 million products. The plant operates 24 hours and seven days a week. There are 3 shifts per day. Closedown period in days (CPD) such as summer break or breaks during Christmas and Easter season accounts for four weeks. Thus, the respective annual production days (APD) are the total days per year (DPY) reduced by the closedown period, as stated in (10).

$$APD = DPY \ - CPD \tag{10}$$

DPY and CPD can also be expressed on a weekly basis considering the days per week (DPW), weeks per year (WPY) and closedown period weeks (CPW).

$$APD = DPW * (WPY - \ CPW) \tag{11}$$

Inserting what is known to equation (11) leads to APD of 336 days as stated in (12).

$$APD = 7 * (52 - 4) = 336\ days \tag{12}$$

Considering the targeted yearly production volume and the ADP hints that average daily production volume is in between 44,643 to 47,619 products. In order to prove that value real production data is compared. In a first step production data is gathered over a period of time and in a second step the number of the yearly production volume of that period is retrospectively gathered.

Based on historical data the yearly production volume of that particular year is 15,311,184. Given the yearly production volume and considering APD, one can calculate the average daily production volume of 45,569 products (referred to as the theoretical average production volume).

The data presented in Figure 16 is collected at the process step final inspection (please refer to Figure 14).

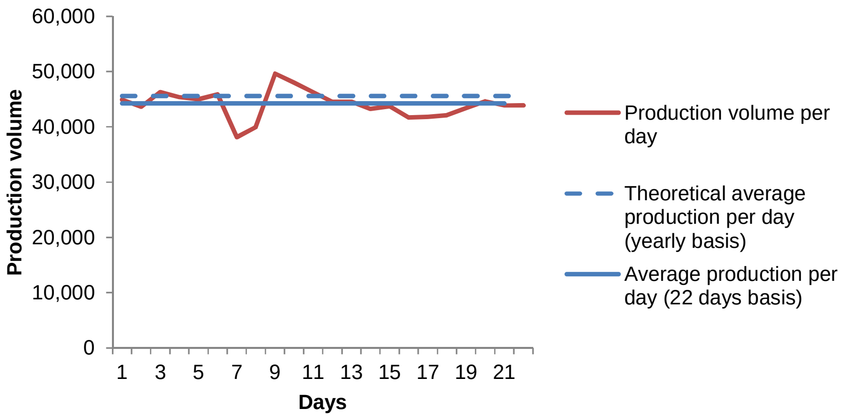


Figure 16: Section of daily production volume on a period of 22 days.

At this production step the product is registered to the information system by the operators at the visual inspection stations. In Figure 16 a section of the daily production volume over a period of 22 days is presented. Based on this sample its average is plotted together with the theoretical average production volume. This average production volume is the one calculated before to accomplish the yearly production volume. Production volume varies significantly from the average production volume per day on a yearly basis in this data section. Less production volume of -15% and higher production volume of +9% are noticeable. In general the mean of this data section of 22 days shows a lower mean than the average daily production volume on a yearly basis. 22 days represent a section of 6.5% considering the APD. Thus, production varies highly on a daily basis.

From interviews with managers of the company this is attributable to a number of reasons and not always predictable. A predictable reason could be the composition of the product mix. Geometrical superior products require a higher cycle time at process step 1 and process step 2 (please refer to Figure 14) than geometrical inferior products. But also other facts like unforeseen bottleneck situation, machine failure or shortage of manpower can restrain. This circumstance demands high efforts to control, plan and adapt the entire manufacturing processes.

Not only production volume varies but also the output of the final inspection process step (please refer to Figure 14 and Figure 15). This effect is discussed in sections 3.1.3.2 and 3.1.3.3.

3.1.3 Analysis of Inspection Performance

In the following three subsections the inspection process performance is analyzed. Firstly, a global analysis of the entire inspection system is presented. This is complemented by analysis of individual performances of operators based on cycle times and appraisal results.

3.1.3.1 Global Analysis

In this section the inspection times of the operators of the visual inspection stations are analyzed. The data of all 24 visual inspection machines of one day is gathered and analyzed.

Figure 17 presents the distribution of inspection times of one particular production day of all operators at the inspection machines. The data stems from the information system and contains 46,890 measurements of inspection times. In order to avoid data dilution only inspection times in between 10 to 180 seconds are considered as valid. This filter results in a sample size of 45,645 elements of inspection times with a minimum value of 11 and a maximum value of 180 seconds.

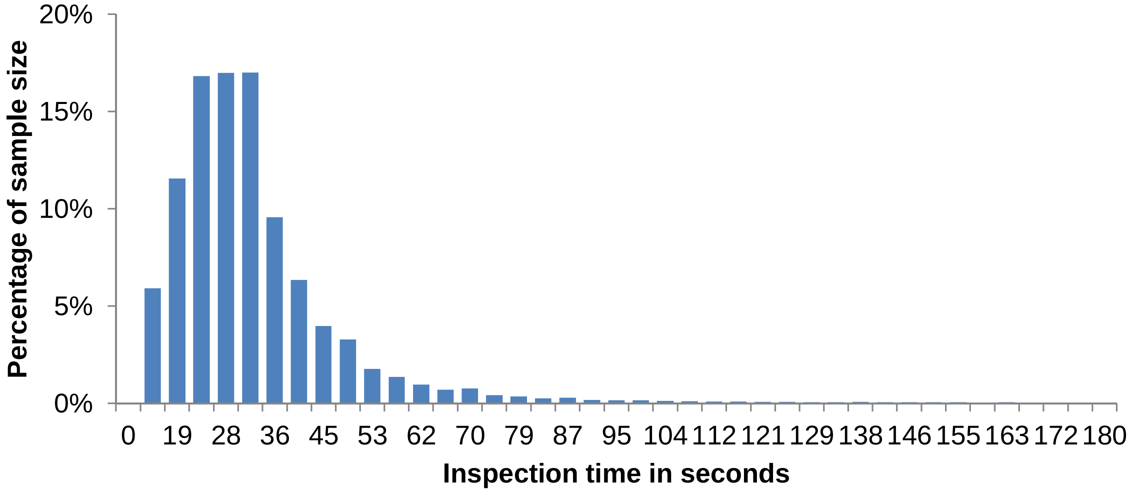


Figure 17: Distribution of inspection time of operators at visual inspection stations.

In order to depict and analyze the data Spread sheet calculation and the input analyzer of Arena (version 13.50.00000) are used. The result in the form of a histogram of 40 intervals is presented in Figure 17. The sample has a mean inspection time of 31.05 seconds with a standard deviation of 17.09 seconds. The analyzer also suggests with the least square error test the similarity to most common distributions which can be seen in Table 9.

Table 9: Fit inspection time distribution to common distribution types.

Function	Sq Error
Erlang	0.00495
Gamma	0.00747
Weibull	0.0139
Lognormal	0.0218
Beta	0.0228
Normal	0.0249
Exponential	0.0344
Triangular	0.0813
Uniform	0.0945

According to Table 9 all listed distributions show in Arena's fit test a square error between 0.004 and 0.1. The squared error calculates the goodness-of-fit according to (13).

$$e^2 = \sum_{j=1}^{J} [\hat{p}_j - p_j]^2 \tag{13}$$

The number of histogram intervals is denoted with J. The variable $\hat{p}_j$ is the relative frequency of the j-th interval of the histogram and p_j is the fitted distribution's probability of the corresponding interval [103]. The lower the value e^2, the better fit is found to a distribution [103].

According to Table 9 the best fit of the data sample epitomizes the Erlang distribution, followed by Gamma, Weibul and Lognormal distribution. For further analysis in the simulation model in 3.3 the lognormal distribution is used for the inspection task times. Arena's user guide recommend the lognormal distribution for the representation of task times whose distribution is skewed to the right [104].

3.1.3.2 Individual Performances of Inspection Times

While the previous section analyzed inspection times of all visual inspection machines this section analyzes the performances on an individual basis of the operators. In this context data of 24 operators at the visual inspection machines is analyzed upon their individual inspection time performances. The data sample is gathered of five consecutive days and illustrated in Figure 18. Details of the sample size, mean values and standard deviations can be found in Appendix I.

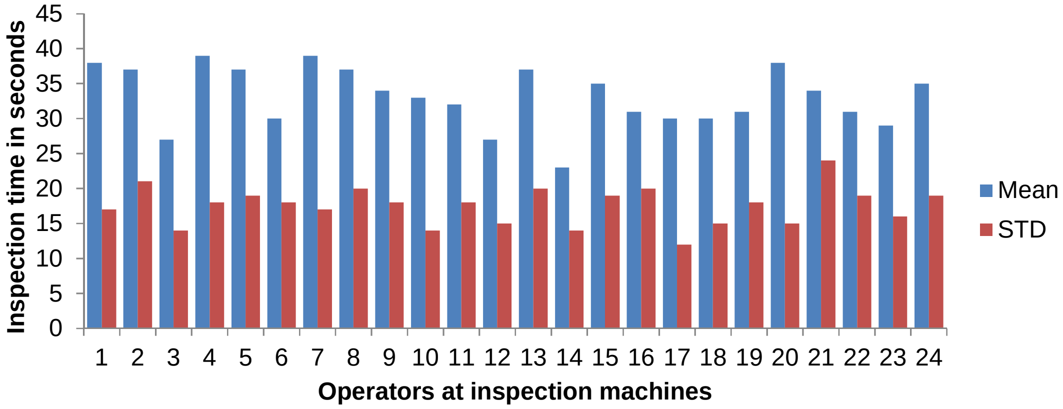


Figure 18: Inspection times of individual operators at visual inspection machines.

Figure 18 depicts the inspection times of individual operators at the visual inspection machines. Performances vary a lot among the operators. While minimum inspection mean time is 23 seconds with a standard deviation of 14 seconds the maximum inspection time is 39 seconds with a standard deviation of 18 seconds. Given that data the variation of inspection time is quite high and differs from just a few seconds to up to 3 minutes.

This aspect can be critical since the manual inspection process step is placed in between two automated processes with a more stable cycle time. Nonmatching cycle times can lead to bottleneck situations if the cycle time of the human process step is higher than the cycle time of the automated process step. A lower cycle time of the human process step compared to the automated process step may lead to idle times at the human inspection process.

3.1.3.3 Individual Performances of Appraisal

This section is dedicated to the analysis of the performances of the manufacturing system in terms of quantification of appraisal decisions. The result of the analysis complements the chapter Qualitative and Quantitative Assessment of the Performance. The quantification of appraisal decisions is done globally for the entire inspection system, and locally for individual operators. Hereby, the number of inspected products are of interest and the ratio of inspection decisions for the product to be conforming and nonconforming.

Complementing to Figure 16 the following graph in Figure 19 is presented. Figure 19 depicts the production volume as in Figure 16 composed by evaluation of product to be conforming or nonconforming.

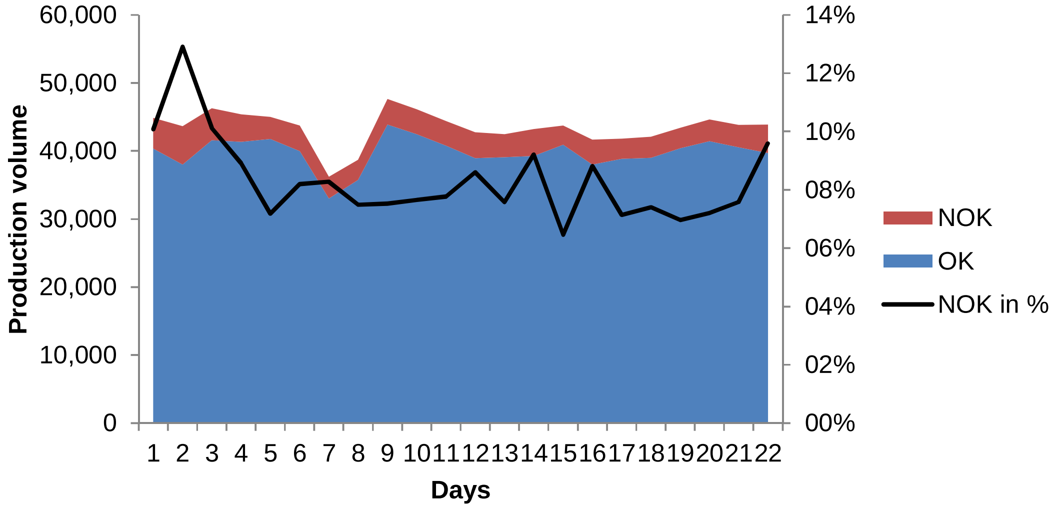
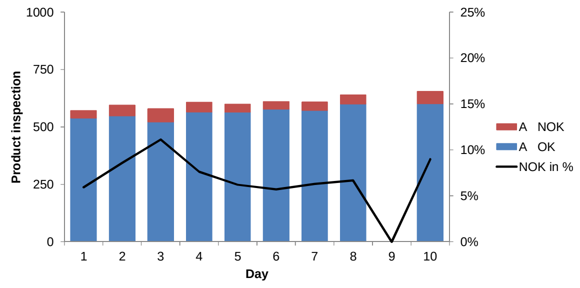


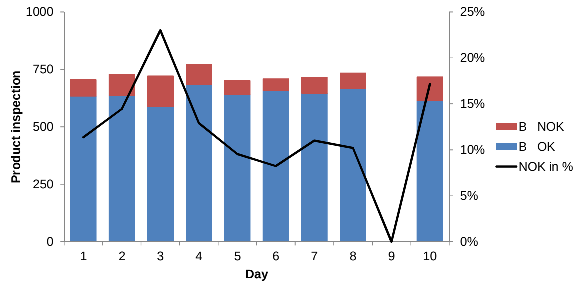
Figure 19: Section of production volume composed by products assessed as OK and NOK.

In addition to the variation of the production volume the ratio of nonconforming product appraisal decisions varies as illustrated in Figure 19. The scope of values of the NOK ratio ranges between 6.5 and 12.9%. The visualization does not indicate a correlation between the production volume and the NOK ratio. The peak of the production volume line does not account the highest NOK ratio and neither does the minimum production value show a minimum in the NOK ratio. According to interviews with managers and operators the quality of the product depends on numerous factors.

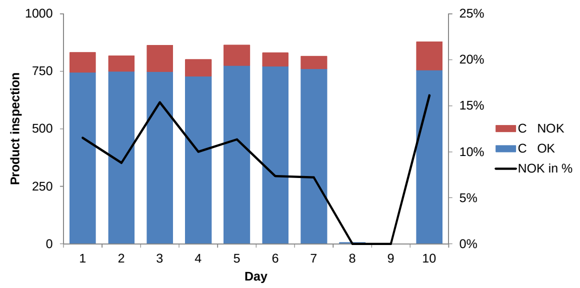
In the following, the appraisal decisions in the perspective of individual operators are analyzed. This refined analysis provides information about the calibration of the operator's decisions. Figure 20 presents the appraisal decisions of four individual operators (operators A to F in Figure 20). In some cases there is information missing, which is attributable to data inconsistency of the data system. The data of Figure 20 a) to d) is a 10 day sample collection of different operators of that specific time period.



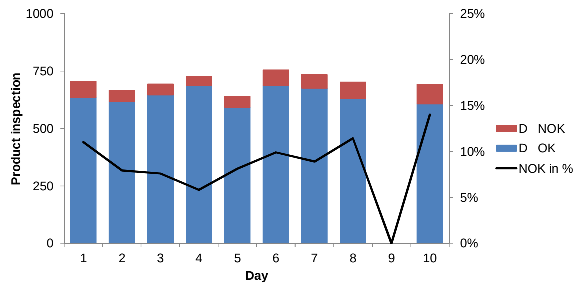
a



b



c



d

Figure 20: a, b, c, d) Individual performances of numbers of product inspection and appraisal decisions.

As one can see the performances vary significantly in terms of number of analyzed products as well as in the ratio of conforming and nonconforming products. Figure 20 a, b and d show a number of inspected products close to 750 per day and Figure 20 c significantly more product inspections per day than 750. On the other hand the rate of NOK% does not seem to be equal among the four operators. Considering that there is an equal distribution of conforming and nonconforming products to the visual inspection stations, the NOK rate variation rather indicates that the operators are not equally calibrated to inspect the product or their quality of decision making varies. Furthermore, in accordance with the previous analysis also the individual ratios of NOK decision do not correlate with the maximum and minimum of each of the operator's product assessment volume. Of course this indication cannot be proven correctly with a sample of only four elements.

However, a study on testing the reliability of the inspection based on a small sample indicates that the calibration is not standardized among the operators.

Figure 21 presents a calibration test done at a company's training session. In that session 30 product samples were assessed upon conformance. Additionally, there were different types of NCs among the nonconforming products. Each test candidate repeated the test 3 times to analyze repeatability besides calibration. Certain thresholds for their performance were defined and expressed in color. Red represents a failed test, yellow is acceptable but requires training and green is a good result. Agreement to standard are the consistently correctly identified products on whether they are conforming or nonconforming. Failure type I represents the rejection of conforming products. Failure type II is the acceptance of nonconforming products. Although, the sample size of five candidates is not significant it indicates that the calibration among operators is not consistently tuned. Having in mind the results of Figure 20 a) – d) and Figure 21 highlights the need to better study and analyze the performance of the inspection system based on the premise that the inspection system is imperfect and characterized by variability.

	Operator V	Operator W	Operator X	Operator Y	Operator Z
Agreement with standard			98.4%		
Failure Type I		0.0%	0.0%	0.0%	
Failure Type II					

Failed test
Acceptable; training required
Passed test

Figure 21: Calibration test of operators at the inspection system.

In order to better study the system first one must develop an understanding of the nonconforming products, which is discussed in the next section.

3.2 Nonconformity Analysis

In the previous section the nonconformance level identified at the inspection system was presented. A nonconformance level usually represents the ratio of nonconforming productions among all inspected products. But in fact the nonconformance level epitomizes an aggregation of categories or types of nonconformities. Hereby, the categories are distinguished by attributes, location on product or other characteristics.

Firstly, an overview of NCs of the affiliated company is given with a quantification of NC categories. Additionally, an approach of the identification of possible NC root causes is presented. In order to select among the most important NCs for further improvement a methodology is provided for prioritization. Both the approach and the methodology can be regarded as quality tools and their applications are presented with case studies.

3.2.1 Overview of the Nonconformities

In the previous section the analysis revealed an NC rate between 6.5 and 12.9% (Figure 19). This section focuses on the composition of the NCs within the total NC rate. Furthermore, information about the recoverability and scrapping is provided.

The affiliated company's catalogue of NCs lists 76 different NCs, which are grouped in categories. Types of categories can be of different nature. Some are related to minor cosmetic or aesthetic issues. Others are severe imperfections which impact driving characteristics or passengers' safety. They are also attributable to categories such as visual, functional and geometrical. Furthermore, the same type of NC, which is located at different spots at the product, can be another category itself.

For a period of 30 days all nonconforming decisions of the product appraisal were analyzed (Figure 22). In total there occurred 35 of the 76 different NCs in that respective period. In this study the NCs are named NC 1 to NC 35 in their descending order of their occurrence quantity.

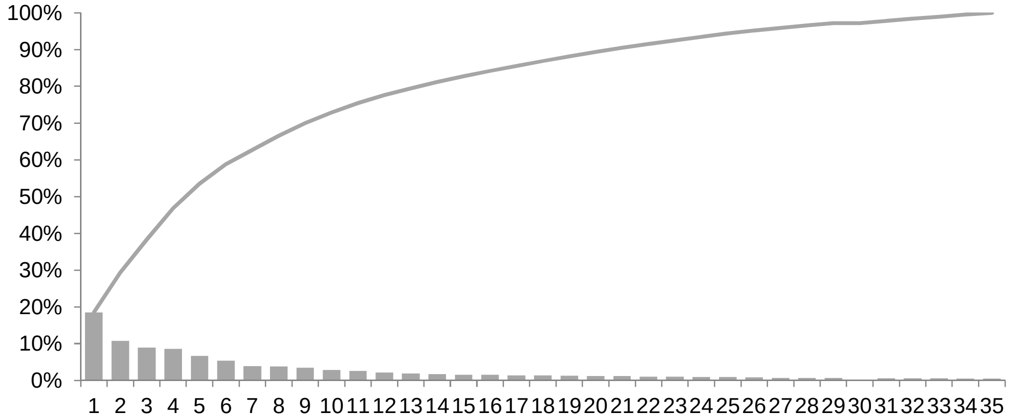


Figure 22: Magnitude of NC occurrences for a period of 30 days.

Figure 23 depicts a selection of the nine most frequent NC occurrences in a waterfall diagram (in the universe of Figure 22). NC 1 is by far the nonconformity with the highest occurrence rate of 19%. NC 2 represents 11%, NC 3 and NC 4 9%. NC 5 to NC 9 occur with percentages between 3 and 7, all other 29 NCs (Rest) sum up to 27%.

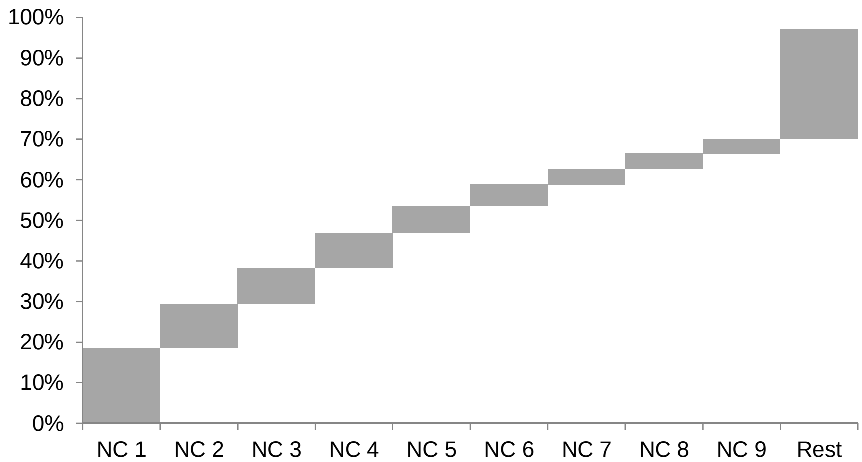


Figure 23: Waterfall diagram of frequency of NC occurrences based on data for a period of 30 days.

In addition to the frequency of NCs the analysis is complemented with the decision of how to proceed after the NC is identified. Figure 24 presents the rework and the scrap rate of each of the 35 NCs. The scrap rate is depicted on the right side of the graph and the rework rate on the left side. The values range from 0 to 100% of the sample size of the respective period. Please note that the rework rate is for the pure purpose of illustration presented with negative values and for interpretation it must be multiplied with -1.

There are also other possible decisions besides rework or scrapping, which is why the sum of the rework and scrap rate do not add up to 100% for some NCs. Other possible decisions could be 'released' because the product was incorrectly classified as nonconforming, among others.

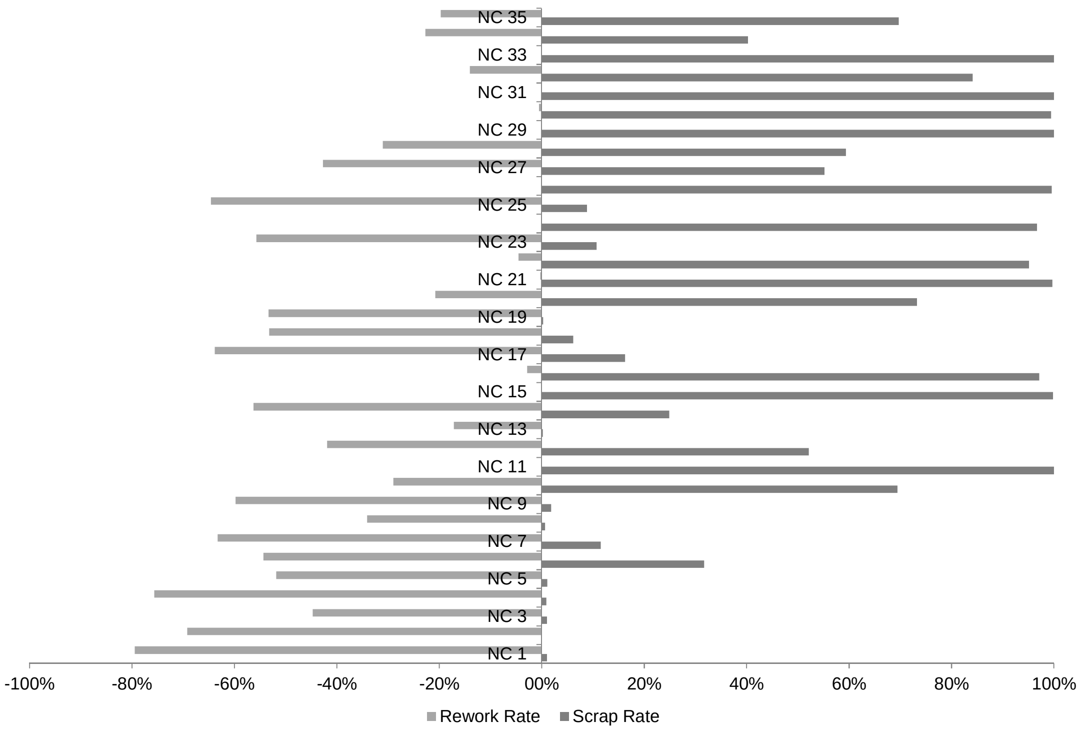


Figure 24: Scrap and rework rate of NCs based on data of a period for 30 days.

The presented graphs in Figure 22 to Figure 24 present a snapshot of the particular period of data analysis. This information provides a first overview of the NC occurrences and their corresponding scrap and rework rates. NC 1 to 5 are the ones with the highest occurrence rates but show one of the lowest scrap rates. Rework rates of those first five NCs are rather high in comparison to the entire dataset.

In order to improve the nonconformance level one must identify and eliminate root causes of the individual nonconformity. Hereby, it is important to prioritize among a given set the most promising NCs that should be selected for further improvement projects. The following two chapters provide approaches to identify possible sources of NC causes and to prioritize the NCs to be selected for further improvement projects.

3.2.2 Root Causes Analysis

In this subsection an approach is presented to identify possible root causes of NCs. The approach can be regarded as a quality tool. The application case of this approach's methodology offers too many variables to be adequate for statistical analysis and visualizations of traditional quality tools. These traditional quality tools such the ones presented in 2.2 do not serve as evaluation instruments. The increased use of information technology in mass production entails more data availability but also demands a great deal of data processing, interpretation and presentation.

Occurring NCs at machines within the production steps are aimed to be identified for further investigation of root causes. Hereby, the traceability of products in mass production with numerous machines at several production steps is highly depending on the level of implementation of information technology. Additionally, this becomes only transparent depending whether efforts for data analysis, interpretation and visualization are done. Knowledge Discovery in Databases (KDD), as presented in 2.2.1.1, for example offers a general framework consisting of sub-elements to generate knowledge from a dataset [37]. A core element is data mining (DM), a method with the aim to identify patterns [37]. The developer who uses this method has a high degree of freedom for using the kind of method as the DM step.

This approach developed is validated through an application case from the affiliated company. The study presented relates to a real industrial problem and refers to the process step 1 and process step 2 (in the following denoted as step n-1 and n) of Figure 14. Quality related data of the two consecutive manufacturing process steps is evaluated and visually represented in a color highlighted matrix. These matrices may identify the source of origin that caused the NCs to emerge. This is done by including the total number of NC occurrences, measuring their concentration among the machines and highlighting in different shades the machines with the highest incidents. The visualization takes into account production steps, production volume and nonconformities that occur at the machines within the production steps. However, the source of origin is not identified and must be further investigated for confirmation.

Results are of interest for academia and practitioners. Different disciplines such as IT, quality and economics are consolidated. The integration of an economics concentration measure into a KDD methodology can be used as a quality tool for quality engineers to identify possibilities to improve processes in mass production with diverse NCs.

This approach presents an efficient method for treating and visualizing data related to process quality, namely NCs that are concentrated to single machines of two consecutive production steps.

3.2.2.1 Background

The approach presented in this section builds on the foundation provided through TQM, quality tools and pattern identification provided in 2.2 and some of its sub chapters. The data mining algorithm in this approach used is an applied statistical concentration measure – the Herfindahl-Hirschman index (HHI).

The Herfindahl-Hirschman Index (HHI) also referred to as the Herfindahl Index is a method to measure concentration [105]. Unaware of Hirschman's published work Herfindahl developed a similar method of measuring concentration at a later date ([105], [106] and [107]). The equations are identical with the only difference of the square root of Hirschman's index on Herfindahl's equation [106]. Herfindahl's equation is depicted in (1).

The index is the sum of the individual market shares of the participants in a specific market. Thus one can state:

$$HHI = \sum_{i=1}^{n} s_i^2 \tag{14}$$

With

$$s_i = \frac{x_i}{\sum_j^N x_j} \tag{15}$$

The index is originally used in economics to measure competition in the marked and the effects of mergers or to measure concentration of income of households [80]. It is an adopted method of the department of Justice and Federal Reserve and currently in use to analyze merger intents [80].

Transferring this sense into the realm of quality can lead to the following understanding: Each imperfect process of a production step produces output – products with NCs – and the concentration to single machine among the total number of producers is measured. For every production step (n-1 and n) the concentration of every single NC is measured. A high HHI is referring to a high concentration, which can be understood that the great majority of NCs is produced by (a) single machine(s). Complementing to the HHI a visualization of all machines with their NC occurrences may highlight the critical ones and might even help in identifying root causes. This has to be proven after the investigation of root causes.

KDD in engineering and quality related topics is well established and known. However, data mining algorithms are plentiful and there is no strict definition for existing models. This approach integrates a well-known statistical measure from the field of economics as the data mining algorithm within the KDD methodology. When applying the suggested method on a dataset it can be used as a quality tool for fault detection in manufacturing.

3.2.2.2 Pattern Identification Methodology

In order to improve production processes and learn from data an adapted methodology for pattern identification is suggested. The resulting patterns provide the basis for interpretation and knowledge creation. Firstly, one can identify which NC occurs concentrated at individual machines. Secondly, one can identify at which individual machines specific NCs occur most. Additional knowledge serves to highlight possible origins of NCs.

To obtain results one must first gather quality related data of the manufacturing process, namely recording the NCs of the production processes of relevance. The data of relevance must include information about the machines that the product passed of all the relevant production steps and the type of NC that was identified at the inspection station. The applied methodology in Figure 25 is an abbreviated and adapted KDD methodology as previously presented in Figure 7.

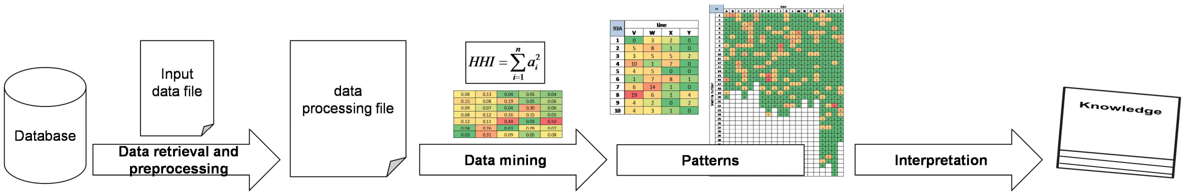


Figure 25: The methodology of the study.

Firstly, one must gather data over a determined period of time. In order to retrieve data in a reliable manner the format of the input data file must be defined. When having the input file the preprocessing of data can be started. This includes spread sheet calculation which must be tailored or integrated to the previously obtained input data file. In this approach the Herfindahl-Hirschman index is the measure that serves as algorithm for the data mining sub-step.

The preprocessed data file provides information for every single NC: the number of incidents, the appraisal decision and the machines the product had passed during production as presented in Table 10.

Table 10: Retrieved data input file from database.

		Step n-1		Step n		Inspection		
Barcode	**Machine**	**Date**	**Time**	**Machine**	**NC type**	**Decision**	**Date**	**Time**
...		...		...		...		
1***622	V1	2010-12-01	02:32:27	A16	NC15	Scrap	2010-12-01	00:11
1***699	X9	2010-12-01	00:04:53	R12	NC3	Repair	2010-12-01	00:32
1***244	Y8	2010-12-01	00:03:38	G19	NC2	Repair	2010-12-01	00:33
...		...		...		...		

With basic calculations one can compute the occurrences of NCs according to machines on basis of the retrieved data as presented. This results in a matrix with machine number and NC type filled with the number of incidents as presented in Table 11.

Table 11: Preprocessing of data to identify the number of occurrences according to machines.

Step n-1	NC1	NC2	...	NCn	Step n	NC1	NC2	...	NCn
Machine 1	x	y	...	z	Machine 1	x	y	...	z
Machine 2	...	...	...	...	Machine 2	...	...	...	...
...	...	...	...	...	...	...	...	...	...
Machine n	u	v	...	w	Machine n	u	v	...	w

Applying the statistical formula (14) and (15) to the tables one can calculate the HHI for a specific NC for one production step. After calculating for all NCs the HHI for each production step one gains information about how concentrated NCs occur at single machines. A specific visualization shall help in identifying the NCs with higher concentration to production machines within each production step.

The visualization will be illustrated using an application case in the next section.

3.2.2.3 The Application Case

The suggested methodology in section 3.2.2.2 is applied to an application case of the affiliated company as introduced in 3.1.

3.2.2.3.1 Problem Description

Figure 26 illustrates the production steps and the input of information into the database. At the last two production steps before the inspection station corresponding data is input into the database. Please note that in this section step n refers to process step 2 of Figure 14 (step n-1 refers to process step 1). This data contains information about the specific production machine, the involved operator as well as time and date.

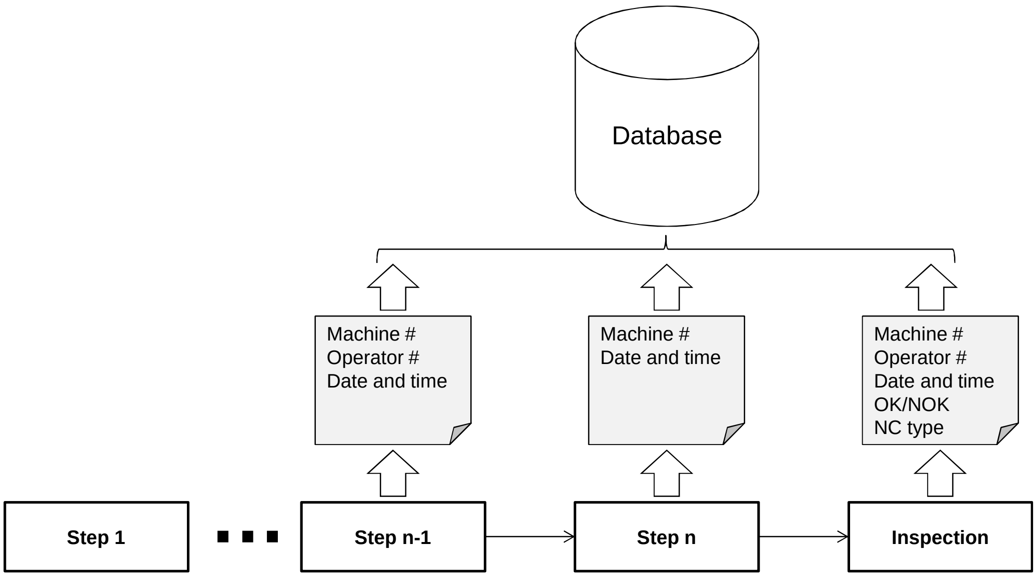


Figure 26: The production flow and data input to the database.

3.2.2.3.2 Overview of the NC Concentration

After applying the tool's methodology one can build the tables as illustrated hereafter. The visualization in the form of patterns consists of two parts. Firstly, the concentration of a specific NC among the machines of each of the two production steps is calculated. This gives general information about whether a specific NC appears concentrated at individual machines within one production step. This is illustrated in Table 12. Secondly, the concentration index number of every NC for the two production steps is compared. This gives information about whether the NCs are very common and related with several machines or whether the NCs are appearing very concentrated to single machines.

Table 12 presents the concentration of all NCs for the two production steps. The numbers in the cells are the HHI results for each NC at the two production steps. Results for step n-1 are depicted on the left and for step n on the right side of Table 12. Each field is the concentration of NC incident of one specific NC of a production step.

Table 12: The HHIs of production step n-1 and n according to the NCs.

	a	b	c	d	e
1	0.08	0.13	0.04	0.05	0.04
2	0.15	0.08	0.19	0.05	0.06
3	0.09	0.07	0.04	0.30	0.06
4	0.08	0.12	0.16	0.15	0.05
5	0.12	0.11	0.44	0.03	0.50
6	0.04	0.26	0.03	0.09	0.07
7	0.03	0.31	0.09	0.05	0.08

Step n-1

	a	b	c	d	e
1	0.03	0.05	0.01	0.01	0.03
2	0.05	0.05	0.02	0.07	0.02
3	0.04	0.02	0.01	0.07	0.03
4	0.01	0.02	0.04	0.03	0.01
5	0.06	0.02	0.09	0.01	0.13
6	0.00	0.11	0.01	0.03	0.08
7	0.00	0.08	0.03	0.01	0.04

Step n

Not concentrated
Moderately concentrated
Highly concentrated

Table 13 provides information about which NC corresponds to the HHI presented in the fields of Table 12 by comparing the horizontal and vertical index numbers and letters. NC18 in field '4c' for example has an HHI of 0.16 in step n-1 and an HHI of 0.04 at step n. Both numbers are not comparable with each other because the numbers of machines are different for the two production steps. However, within one production step they do become comparable with each other. NC33 and 19 (Field 5e and 5c) show the highest HHIs for step n-1. NC33 and 13 (Field 5e and 6b) show the highest HHIs for step n.

Table 13: Corresponding NCs for HHI in Table 12 for step n-1 and n.

	a	b	c	d	e
1	NC1	NC8	NC15	NC22	NC29
2	NC2	NC9	NC16	NC23	NC30
3	NC3	NC10	NC17	NC24	NC31
4	NC4	NC11	NC18	NC25	NC32
5	NC5	NC12	NC19	NC26	NC33
6	NC6	NC13	NC20	NC27	NC34
7	NC7	NC14	NC21	NC28	NC35

3.2.2.3.3 Result Tables of the Production Steps

Production step n-1 consists of fewer machines than the ones in production step n. The machines at each production step operate in parallel and exactly one machine at each production step is passed for the product to be produced. The route that the product takes from one production step to another depends on the set-up configuration of the machines. Different configurations allow the production of products that vary in size, composition and shape.

Following the suggestions of Table 12 the highest NC occurrences shows NC33 for both production steps. The NC occurrences at the machines are delineated in Figure 27. Each field of the matrices represents one specific machine. The machines are located in lines and are numbered. Step n-1 consists of four lines (V, W, X, and Y) each with 10 machines. Step n consists of 20 lines (A, B, …, T) each equipped with machines varying in number between 16 and 38.

The left matrix in Figure 27 presents the number of occurrences of NC33 for every machine of production step n-1. As one can see machine number Y2 is related with 99 NCs among a total number of 141 NCs. All other machines of this production step show numbers of occurrences between zero and four. The right matrix in Figure 27 presents the number of occurrences for every machine of production step n. In comparison to step n-1 the NCs occur more fragmented. Machine number R8 has the highest number of NCs (47). Machine number R7, R14 and O22 show number of occurrences of 15, 18 and 13. All other machines do not produce products with NCs or only few.

The obtained results highlight the high concentration of NCs to machine Y2 of production step n-1. Thus, the number of occurrences is very concentrated to one single production machine and steps for further analysis of root causes of the NC must be done. A possible tool for doing that can be the cause and effect diagram from Table 4. This lists all possible factors of contribution such as operator, machine, method or material and one can observe and investigate with this structured help the root cause if there is one to find.

A first observation may indicate that this machine (Y2) is the main contributor of the NC and that the root cause might be found when this machine is further analyzed. However, this information shall be taken as a direction and invite for further investigation and must be considered cautiously. Additional information is required to gain higher certainty of this assumption. The methodology indeed does take into account the total number of a specific

NC. But it does not consider the total number of the products based on the set-up configuration of the production machines. This means the method does only take into account NC types regardless of further product features, such as size, shape or composition.

NC 33	Line			
	V	W	X	Y
1	2	0	1	0
2	1	3	3	99
3	3	0	2	1
4	1	0	0	0
5	1	0	0	0
6	4	0	1	0
7	1	0	1	2
8	0	0	1	0
9	0	1	3	2
10	4	4	0	0

NC33	Line																			
Machine number	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0
2	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	1	0	0	0
3	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
4	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0
5	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	15	0	0
8	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	47	0	0
9	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	2	0	0	0
10	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
12	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	6	0	0
14	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	13	0	0
15	0	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0
16	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	2	0		1	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0		0	0	0	0	0	0	1	1	0	0	0	1	0	0
19	0			0			0	1	0	0	0	1	0	0	2	0	0	0	0	0
20	0			0			0	0	0	0	1	0	0	0	0	0	1	0	0	0
21							0	0	0	0	0	0	0		7		0	0	0	0
22							0	0	0	0	0	0	0		18		0	0	0	0
23								0		0	0						0	0	0	1
24								0		0	0						0	0	0	0
25																	0	0	0	0
26																	0	1	0	0
27																	0	0	0	0
28																	0	0	0	0
29																	0	0	0	0
30																	0	0	0	0
31																	0	0	0	
32																	0	0	0	
33																	0	1	0	
34																	0	0	0	
35																	0	0	0	
36																	1		0	
37																			0	
38																			0	

Figure 27: Result presentation of process step n-1 (left) and n (right).

Furthermore, when comparing the two matrices in Figure 27 there is a mismatch in total numbers of NCs. While step n-1 has a sum of 141 occurrences of NC33, step n shows 155 occurrences. Theoretically both numbers should match since every product passes exactly one machine at each step. This inconsistency has to do with incomplete datasets, which are attributable to technical defects of scanned barcodes or to a neglect of data entry by operators, among others.

Similar matrices as presented in Figure 27 are obtainable for all other NCs presented in Table 13 and ready for interpretation to discover knowledge. But presenting these figures would exceed the frame of this approach.

3.2.2.4 Remarks

The analysis of section 3.2.2 proposes a methodology to help analyzing root causes of NCs. Discovered knowledge, which is visually represented supports to identify possible root causes in mass production. An economic concentration measure (HHI) is integrated as the data-mining element of the KDD method. The proposed methodology can be used as a quality tool and is validated by an application case from the automotive industry. Data tables are generated with different cell shadings according to the concentration of specific incidents. An incident in this context is an occurrence of a specific NC. These tables may help in disguising main contributors of NCs exposing them to the user to be further investigated.

Results indicate that with the applied visualization technique it is possible to identify single machines that are highly related with specific NCs and may be the originator. Further investigation of the likelihood of being the originator of NCs is required as the next step.

The methodology integrates several disciplines: IT, quality and economics. A well-known and established economical concept finds in quality an additional field of application. Quality engineers of industrial companies may find interest in using the tool to identify root causes in mass production with numerous machines and diverse NCs. According to the presented results the visual representation of the data helps to quickly understand which NCs show the highest concentrations to machines at different production steps. The highly visual results ease the interpretation and further analysis to constantly improve production quality.

While initial findings are promising, further research is necessary. As a start, the success rate of being able to identify the root cause of an NC after having highlighted a possible contributor must be identified to further validate this tool. This tool is currently developed to be used offline. With further development and integration to the installed IT system of a company it can turn into an online tool. Additional development can even automatically alert responsible persons when a critical value of concentration is exceeded and further investigations of root causes become attractive. Furthermore, instead of presenting the visualized concentration indices for the two production process steps separately their integration into one visualization index could be explored.

As this approach demonstrates combining knowledge of different disciplines can result in new emerging methods, tools and knowledge. Cross- and interdisciplinary research is highly encourage.

3.2.3 Portfolio Prioritization

Targeting Zero Defects in production is an often sought state in any company but more crucial for the ones aiming to achieve world class manufacturing performance. One lever to continuously ameliorate processes is to focus on a specific NC and to identify and eliminate its root causes. Among all NCs that are found the selection and prioritization of the right ones is key for improving quality efficiently. This is due to limited resources for investigation and rectification of the problem and to take multiple objectives into consideration.

Within the Total Quality Management (TQM) realm, as introduced in 2.2, suggestions are provided on how to investigate root causes of NCs and on how to prioritize NCs as well. However, there is no published approach based on multi-attribute criteria to monitor, prioritize and select NCs for further investigation upon taking into consideration multi-attributes.

The study in this section intends to fill this gap by presenting a novel approach to track and prioritize NCs with weighted multi-attributes. This approach promotes selective tracking among a set of NCs fostering its prioritization for the selection of future improvement projects. The approach has a multi-attributes weighting engine based on FMEA (Failure Mode and Effect Analysis) and Pareto principles. This research is a contribution to existing quality tools in the TQM literature as presented in 2.2.1. Results indicate that the approach presented in this study behooves to be not only used within the quality realm by practitioners such as quality engineers but can also be applied for any portfolio prioritization problem.

A background of relevant topics was given in 2.2.1.2. The approach for prioritizing NCs is presented in the following. After illustrating the notional model proposed, instructions for devising the approach is provided and a real-based data case study from the affiliated company presented. In addition a complementary presentation of NCs is introduced to enhance the understanding of its profile according to quality related attributes. Results are shown, discussed and conclusions drawn.

3.2.3.1 Background

The approach presented in this research is akin to the concept of the Share/Growth matrix (The Boston Box), which was published in 1973 by Henderson [108], a founder of The Boston Consulting Group [109]. In that paper Henderson [108] described how all products of a company's portfolio are plotted in a 2x2 matrix according to single attributes (ratio to market share of the biggest competitor and growth in capital opportunity alternatives). He goes on and includes two divisional lines to divide the matrix in four sections (high growth and large market share; high growth and less market share; low growth and large market share; low growth and less market share). Each section is provided with advice on whether to invest or not.

This concept is taught in academia and is the basis of further developments by industry. General Electric's (GE) Multifactor Portfolio Matrix and the nine box matrix by McKinsey are prominent successors beside several others [109]. It gratifies of a high adoption rate of several companies across industries and is mostly used in corporate planning and strategy, and thus one can conclude that its emergence filled an existing gap. Morrison and Wensley [109] also report the matrix to be a part of curricular in marketing and strategy courses. Identifying product/ strategic business unit (SBU) market positions and assessments and opportunities is one of the major reasons for being taught. They continue and refer to the Share/Growth Matrix to be part of the business language one of the main reasons for its use.

3.2.3.2 Aims and Scope

The main aims of the developed approach were the identification of the most critical NCs that should be prioritized for future improvement projects and to foster the communication of quality related topics to management.

This study presents a novel approach for identifying and prioritizing the most promising NCs among a numerous set based on a selection process of multi-attributes is an actual need. The proposed approach integrates elements of TQM tools such as Pareto diagram and FMEA. A popular concept of the marketing area is adopted to be applied in the realm of quality.

In this particular study two significant contributions are made. First, to support the categorization of NCs, a structured way is developed of defining a weighted multi-attribute evaluation approach. The corresponding attributes are categorized in two groups.

Secondly, in order to support the identification and selection of future improvement projects, a two dimensional matrix partitioned in four sections is created, that allows the positioning of different NCs, according to different weighting strategies, and consequently allowing the prioritization analysis in a structured way.

After a notional model is presented in the next section, an application case of a real industrial company integrated in the automotive supply chain is given.

3.2.3.3 Nonconformity Tracking and Prioritization Matrix

In this section a methodology overview is given. The tool's functionality, the required inputs and generated outputs are explained and discussed.

3.2.3.3.1 Purpose and Overview

The prioritization is of particular interest for manufacturing companies whose imperfect production processes result in a variety of NCs of a given product of their high volume production processes. NCs are displayed in a 2x2 matrix with two weighted multi-attribute axis. One axis targets risk level attributes (x-axis) and the other causes and impacts (y-axis). Thus, in addition to the risk level elements of FMEA NCs are also evaluated in another dimension related to causes and impacts in order to achieve a refined prioritization. This enables the user to identify and select the improvement projects in structured manner and additionally to follow-up the evolution of the improvement projects through a clear representation of the assessment results. The approach can be applied by decision makers of industrial companies with several competing improvement projects. Moreover, the approach can be used for any portfolio decision making problem.

Figure 28 shows the conceptual model of the matrix partitioned in four areas. The top right area (dark shaded) is the "critical" area that contains NCs that are strongly weighted by both multi-attributes. NCs in this area are critical and impose themselves for immediate actions of improvement. The two areas lightly shaded, one positioned on the top left and the other on the lower right side, are in the "to be observed" zone. The development of those NCs should be observed over time and selected for improvement if threatened to turn into a "critical" NC. Individual NCs in these areas can also be selected for improvement projects, if resources are available (or if there are no NCs in the critical area). The lower left quarter is the "controlled" area with NCs ranked low regarding both multi-attributes (not shaded).

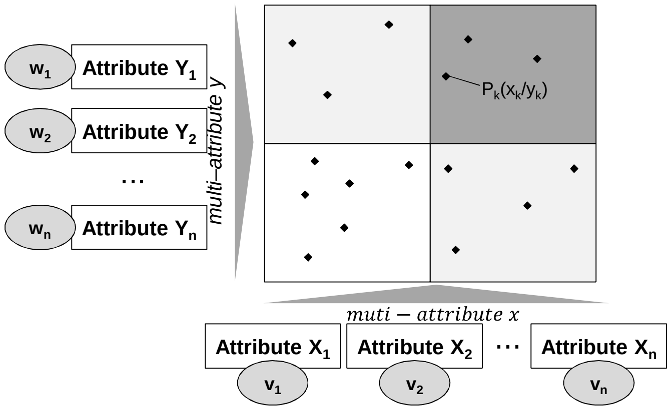


Figure 28: Conceptual model of the matrix with multi-attributes plotted in a 2x2 matrix.

Following the process steps in Figure 29 guides to create the quality tool. Firstly, the attributes that are relevant for the identification of NCs are defined as a basis for selecting quality improvement projects.

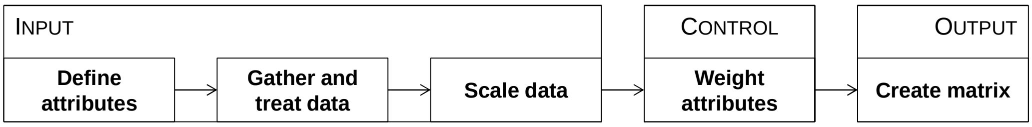


Figure 29: Process steps to develop the quality tool.

Table 14 provides a list, without claiming to be complete, of typical attributes of quality relevant data.

Table 14: List of attributes for creating the nonconformity prioritization and tracking matrix.

Attributes	**Comments**
Risk level attributes	
Occurrences of NCs	Total numbers of NCs in a given period
Severity	Hypothetical impact on safety of a given NC if delivered to and used by the customer
Detectability	The difficulty of detecting a specific NC
Causes and impacts attributes	
Rework rate	The number of products reworked in relation to its number of occurrences of a specific NC
Scrap rate	The number of products scrapped in relation to its number of occurrences of a specific NC
Concentration of NCs at specific production machines	The concentration of occurrences of NCs at specific production machines
Correlation of NCs to a specific product attribute	The occurrences of NCs given a specific product attribute
Cost	Scrap or rework cost of a specific product
Customer complaints	The occurrences of customer complaints that can be related to a specific NC

The attributes that are chosen for creating the nonconformity tracking and prioritization matrix should be mutually exclusive but do not have to be collectively exhaustive. After defining the attributes one must categorize them into two groups. Each group represents the composition of attributes (multi-attribute) of one matrix's axis. The x-axis is composed with attributes related to the risk level and the y-axis with attributes related to causes and impacts. Having defined the attributes and grouped them as a multi-attribute the next step is to gather and treat the data of each attribute. Data can be retrieved from information systems and treated. Hereby quality tools for example or departmental reports can be used. Borrowing from social science the four basic methods for gathering data can be of assistance.

The next step is the scaling of data. The scaling or normalization is required to fit the single attributes in a multi-attribute model aiming a multi-comparison framework. In order to overcome different spectrum of the attribute's data the x_j (y_j) must be scaled as follows, with x_{max} being the highest value of the attribute data and x_{min} being the lowest:

$$x_i = \frac{x_j - x_{min}}{x_{max} - x_{min}} \tag{16}$$

and

$$y_i = \frac{y_j - y_{min}}{y_{max} - y_{min}} \tag{17}$$

After data gathering and setup for further numerical manipulation the proposed tool requires the definition of weights. This allows controlling the importance of the attributes aiming to identify the most critical NCs for different levels or types of quality targets scenarios. The final output consists of a matrix where the several NCs are plotted in different severity zones depending on the strengths given to each weight. These last two steps are described in detail in the following section.

3.2.3.3.2 Formalization and the multi-attribute matrix construction

A lot of possible methods to determine the weights of the attributes can be considered. A rather simple one is to leave this as an input for the user to establish levels of importance, based on his or her preferences given towards the individual attributes. A different approach is to use the weights based on feedback given. Feedback could be the cost of the attribute which are determined prior to modeling the matrix. Based on historical data and cost of the attributes one can calculate the weights. Also company philosophy can be taken into account if certain attributes comply better with mission statements of the company.

Identifying weights based on pairwise comparison as done for instance in the Analytic Hierarchy Process [47], which is used plentifully as one can see in Table 5, is also thinkable.

The objective is to create a scatter chart with elements positioned based on their x and y values, which are composed by other attributes as schematically shown in Figure 28.

One can state:

$$x_k = \sum_{i=1}^{n} x_i * v_i \tag{18}$$

$$y_k = \sum_{i=1}^{n} y_i * w_i \tag{19}$$

With $v_i, w_i \in [0{,}1]$ and $\sum_i^n v_i = 1 \; and \; \sum_i^n w_i = 1$

As a result one calculates positions of elements within the scatter diagram based on weighted attributes: $P_k(x_k; y_k)$.

The farther away from the point of origin of one axis, the more extreme the element is based on its attributes and weights given (please refer to Figure 28).

3.2.3.3.3 Strength and Limitations

The main strength of the approach is the ability of objective decision making, which is based on weighted multi-attributes. In addition to that changing the settings of the weights might result in different matrix graphs and can uncover NCs that should be prioritized, which might have been neglected otherwise. Furthermore, the approach allows monitoring the NCs, which have been selected in previous periods for improvement. If the improvement actions take effect the NCs should recede from the critical area of prioritization.

One has also to mention that the approach is highly illustrative in terms of result representation. The matrix is partitioned in four sections, which makes it intuitive to identify the critical or controlled NCs according to the weighted relevant attributes. The presentation style is analogue to an already established approach in marketing and one can take advantage of the publicity for communicating quality related topics in business language. Lowy and Hood [111] name the simplicity of a 2x2 matrix as one of its greatest characteristics and state that 2x2 thinking improves clarity, honesty and quality of problem solving. Thus, it is in accordance with nowadays trends of visual management.

In addition to that the approach is highly flexible considering the attributes. All inputs are not only interchangeable but also exchangeable with new attributes that are of interest to be taken into consideration for the evaluation.

The proposed approach fills the gap of prioritizing NCs for future improvement projects based on multi-criteria.

A drawback of this approach is that its use is supposed to be an offline tool and thus requires periodical updates. If wanted to act in real time it is upgradable with additional IT development to operate as an online tool according to the on-site IT environment. However, with restriction to flexibility since attributes are then not as easily exchangeable. Moreover, qualitative input data requires reassessments over time on whether the assessments still hold. This means that participating people for qualitative input must be re-interviewed. Besides the previous mentioned objective decision making is at stake when over-weighting one specific attribute and neglecting the others. When doing this the multi-attribute decision making is turned back to a single attribute decision making.

3.2.3.4 Application Case

The case study under analysis was developed on the company as described in 1.1.

For this study the last two production steps are analysed and the data retrospectively retrieved at the inspection process at the end of the manufacturing line. This can be seen schematically in Figure 30. Please note that step n refers to process step 2 in Figure 14 (step n-1 refers to process step 1). Each machine at each production step leaves distinct evidence at the product that is identified and gathered at the IT system. A result of the inspection is an evaluation decision of the product to be conforming or nonconforming to requirements. Conforming products are approved and forwarded to be shipped to the customer. Nonconforming products are registered and characterized by the type of NC and evaluated upon recoverability. In addition, information about the history of production steps is available, containing information regarding the specific machines the product had passed. Both steps n-1 and n in Figure 30 consist of several machines and each product has to pass exactly one machine in each step. Hence, a clear identification which machine of the two production steps is the contributor of the NC is not possible retrospectively at the appraisal of the finished product.

The categories of the NCs match to the ones described in 3.2.1. After having the list of NCs one can generate the NC Tracking and Prioritization Matrix, following the previously mentioned formalization instructions.

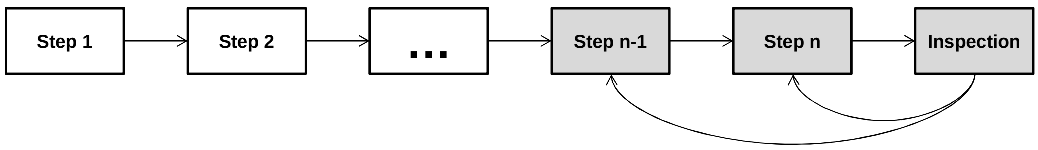


Figure 30: Production process steps of the case under analysis.

3.2.3.4.1 Defining the Attributes

Defining the attributes is the first step of building the matrix. The x-axis is composed with attributes related to the risk level and the y-axis with attributes related to causes and impacts.

Attributes on the x-axis comprise the attributes of the known systematic method FMEA: Frequency of occurrences, severity and detection probability. Attributes on the y-axis are composed by scrap rate, concentration of NCs to single machines and customer complains related to the NCs. This approach considers, in addition to the important risk level attributes, the company specific attributes related to the installed quality system.

The proposed attributes in Table 15 are all data related to quality and represent production related data regarding the NCs. The selected data stem from both quantitative and qualitative data. The selection of the remaining attributes besides the ones of the FMEA method is based on expert interviews and validation cycles and were all evaluated to be important.

Table 15: List of attributes of the application case.

Attribute	Attribute Name	Type of data	Comment
X_1	Frequency of NC occurrences	Quantitative data	$X_1 = \sum x_{1,i}$ The number of frequency of occurrences of a specific NC.
X_2	Severity of NC	Qualitative data	Hypothetical impact on customer's safety if NC remains undetected, delivered to customer and used.
X_3	Detection	Qualitative data	Likelihood of a specific NC to not be detected by the inspection system.
Y_1	Concentration of NCs to machines (Herfindahl-Index)	Quantitative data	$Y_{1,i} = \max(HHI_{1,1}; HHI_{1,2})$ $with\ HHI_{1,i} = \sum_{i=1}^{N} s_i^2 \quad and\ s_i = \frac{x_j}{\sum_j^N x_j}$ HHI represents the concentration of an individual NC to single machines.
Y_2	Customer evaluation	Quantitative data	Data analysis regarding customer complaints and warranty claims, which are related to specific NCs.
Y_3	Scrap rate	Quantitative data	$Y_{3i} = \frac{y_j}{\sum_j^N y_j}$

Frequency of occurrences is the number of occurrences of one specific type of NC among the total number of all occurring NCs. It is an important indicator to quantify the magnitude of the occurrences of NCs. If the quality tool Pareto diagram already exists its data can be reused as a model input and the corresponding data can be directly scaled as previously described. Figure 31 presents the Pareto diagram of the NCs in the application case. All 35 different NCs are presented with their corresponding number of occurrences.

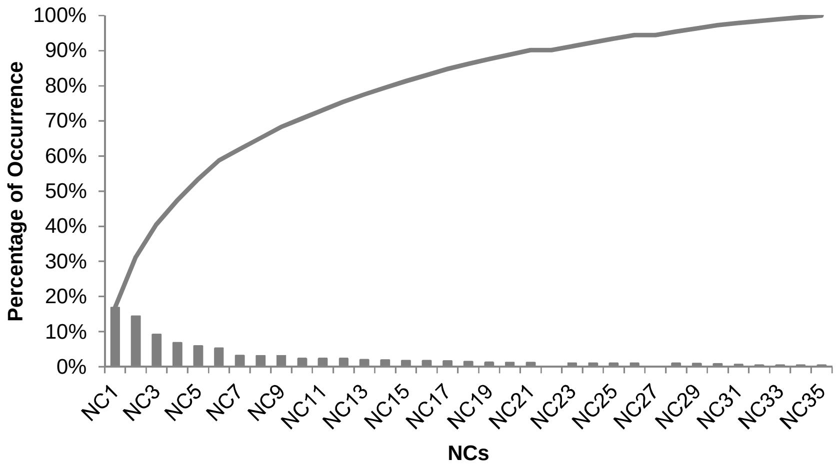


Figure 31: Figure 4. Pareto diagram of NCs of the application case.

The severity attribute is addressing the hypothetical impact on customer's safety if a by the inspection system undetected product with an NC failed in use by the customer. The harm is estimated on a Likert scale based on interviews with experts from production, quality and engineering departments. Although, the information is based on rough estimates of expert interviewees and biased by subjectivity it provides very important information about consequences if NCs unintentionally pass the inspection system.

The detection attribute is related to the effectiveness of the inspection. Data was gathered through expert interviews from the company's quality department. The experts were asked to rate the likelihood of each specific NC to not be detected by the inspection system on a scale of 0 to 10. The value 0 represents that the NC is always detectable and the value 10 indicates that the NC is impossible to be detected. This is an important attribute as selection and prioritization criterion with the goal to diminish the NCs with a high likelihood to be undetected by the inspection system.

The next attribute is the concentration of NCs to machines. In order to devise this attribute results of the approach of section 3.2.2 are incorporated. Thus the concentration or HHI respectively provides an indication of how concentrated a single NC occurs at individual machines of the previous production steps. The approach assumes that the higher the HHI value the more NCs do concentrate to single machines. Therefore, it provides an incentive to eliminate its root causes at the machines with the highest concentration of NCs. Figure 32 depicts the maximum HHI value of two consecutive production steps of the application case. Additional data processing and visualization yield information to which exact machine specific NCs are concentrated on. Considering this the attribute provides indication for a possible source of root causes at machines, which are well worth to further investigate. It is also in accordance on the company's standard of continuous improvement.

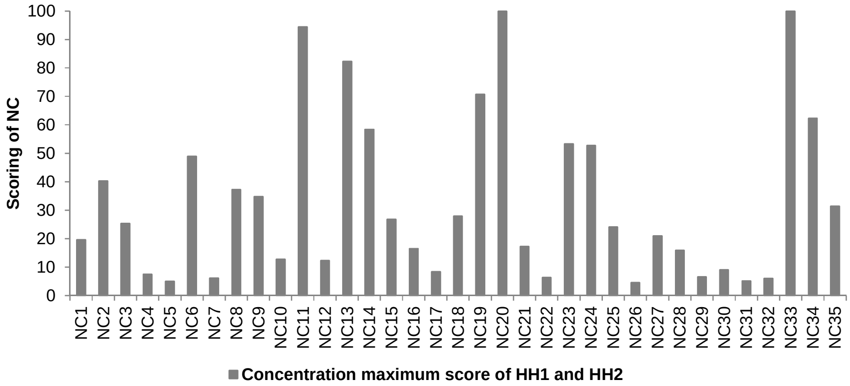


Figure 32: Maximum value of the HHI in % of two consecutive production steps of the application case.

The customer evaluation attribute is related to customer complaints and warranty data that is collected by the company. This data must be related and if necessary adapted to the NC coding of the inspection. A Pareto analysis of the customer complaints can serve for analysis. This attribute is important and in accordance with the company's quality system. The company claims customer complaints and warranty rates to be low due to possible penalties for delivering nonconforming products and reputation loss.

The scrap rate attribute is the ratio of positive decisions to scrap the product to its total number of NC occurrences of a given period. The total number of NCs includes all incidents such as scrap, rework or false negative product evaluation. Figure 33 depicts scrap rate of the NCs of the application case of a given period. Some NCs show a 100 per cent scrap rate, which means that the product is scraped every time an NC is detected by the inspection system. This is inefficient and expensive to the company due to production losses. Furthermore, focusing on reducing scrap is an important attribute to consider and used to be considered as one of the main criterion for selecting improvement projects by the company.

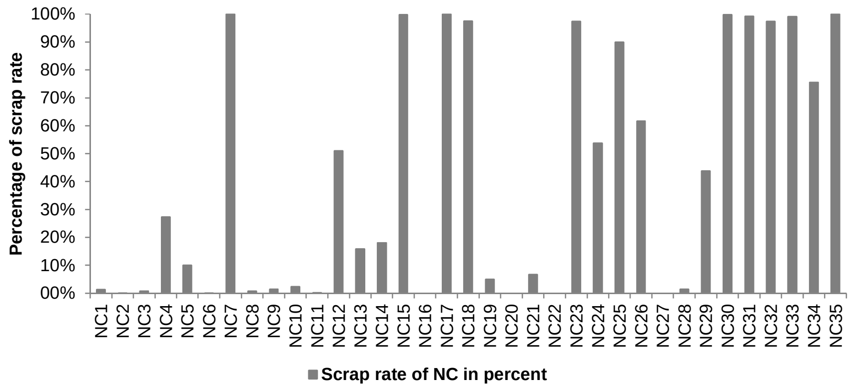


Figure 33: Scrap rate of NCs of the application case.

3.2.3.4.2 Gathering and Treating Data

After defining the attributes, the production resident data is computed to calculate the scores of the relevant attributes as presented in Table 15. At each production step the product has a specific identifier in form of a barcode. At every production step information is input to the database with machine number, operator number, time and date. At the end of the production process the product is evaluated by the inspection process upon conformance. If stated as nonconforming the type of NC and the decision of whether to scrap or recover the product is recorded. After retrieving the relevant data from the database it is treated according to the formula given in the previous sections. The result of the data treatment can be seen in Appendix II.

3.2.3.4.3 Scaling Data

If data is gathered and treated one has to scale it for it to fit into a composed multi-attribute axis. Within the data sample of an attribute the maximum and minimum values are identified and every data set element is scaled based on the presented equations (18) and (19).

Table 16 provides an example of scaling based on those scaling equations. In the presented application case, the gathered data of the attribute frequency of NC occurrences has a maximum of 7026 and minimum of 0 (see Appendix II). Thus the scaling equation can be assembled as follows:

$$x_i = \frac{x_j}{7026} \tag{20}$$

Appendix II provides a full overview of all attributes together with the corresponding scaling information.

Table 16: Extraction of scaling data.

	Occurrences	Severity	Detection	HHI_1	HHI_2	Customer complaints	Scrap rate
Max	7026	4.67	10	0.13	0.68	1	1
Min	0	0	0	0.0038	0	0	0

3.2.3.4.4 Weighting the Attributes

The number of combinations of allocating weights to attributes is infinite and so are the outcomes of these particular matrices.

In this study a two-step approach is proposed. Each contains three sub-steps, to generate result matrices. In the first step equal weights are given to the attributes at 'risk level' x-axis. In the second step the attribute Severity is given full weight because safety is the most important attribute at the 'risk level' x-axis. The following three sub-steps contain setting full weight to each of the 'causes and impacts' y-axis. Thus, in each step three matrices are generated, which yields six matrices in total.

The proposed strategies to generate results are summarized in Table 17. Each strategy presented has a specific setting of weights according to what is sought as mentioned in the comments. The weights v_i refer to the attributes x_i and w_i to the y_i attributes in equations (18) and (19).

Table 17: Strategies to set weights to generate results with the tracking and prioritization tool.

Strategy	v_i	w_i	Comments
1.			Average weighting of 'risk level' x-axis
a.	$v_i = \frac{1}{n} = \frac{1}{3}\ (for\ n = 3)$	$w_1 = 1;\ w_2 = w_3 = 0$	Identify NCs with average weighting of risk level x-axis and a high concentration of NCs to machines
b.	$v_i = \frac{1}{n} = \frac{1}{3}\ (for\ n = 3)$	$w_1 = 0;\ w_2 = 1;\ w_3 = 0$	Identify NCs with average weighting of risk level x-axis and a high numbers of customer complaints
c.	$v_i = \frac{1}{n} = \frac{1}{3}\ (for\ n = 3)$	$w_1 = w_2 = 0;\ w_3 = 1$	Identify NCs with average weighting of risk level x-axis and a high scrap rate
2.			Maximum weighting of one attribute Severity
a.	$v_1 = 0;\ v_2 = 1;\ v_3 = 0$	$w_1 = 1;\ w_2 = w_3 = 0$	Identify NCs that are severe and highly concentrated to machines
b.	$v_1 = 0;\ v_2 = 1;\ v_3 = 0$	$w_1 = 0;\ w_2 = 1;\ w_3 = 0$	Identify NCs that are severe and have a high number of customer complaints
c.	$v_1 = 0;\ v_2 = 1;\ v_3 = 0$	$w_1 = w_2 = 0;\ w_3 = 1$	Identify NCs that are severe and have a high scrap rate

The proposed strategies should not confine the user of the approach to extract data differently. For instance one could perform the same analysis for each of the remaining two attributes of the y-axis as done in strategy 2a, 2b and 2c in Table 17.

3.2.3.4.5 Matrix Output – Results and Discussion

In this section the results of the presented approach in the context of the case study are presented. Herby the NCs are plotted in a 2x2 matrix on composed axis ordinates with different weights and portrayed in Figure 34 to Figure 39.

3.2.3.4.5.1 Average Weighting:

To begin obtaining results the first strategy of Table 17 is followed and the weights of the risk level axis are equally weighted. With equal weights at the 'risk level' axis graphs are generated with full weights of each attribute at the 'causes and impacts' axis. This manner of setting weights can be considered as a refined FMEA selection. All NCs passing the score of 50 on the 'risk level' axis are already selected by FMEA but need to additionally achieve high scores on the 'causes and impacts' axis. The results are presented in Figure 34 to Figure 36.

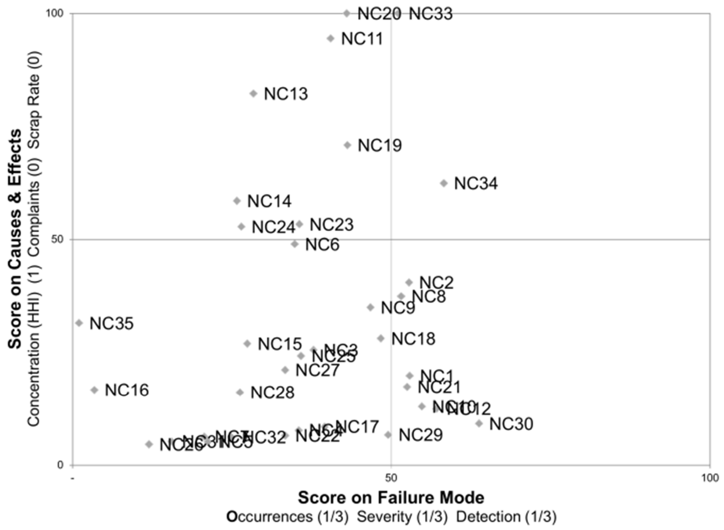


Figure 34: Matrix result: All attributes of x-axis with average weights and full weight to concentration of NCs at y-axis

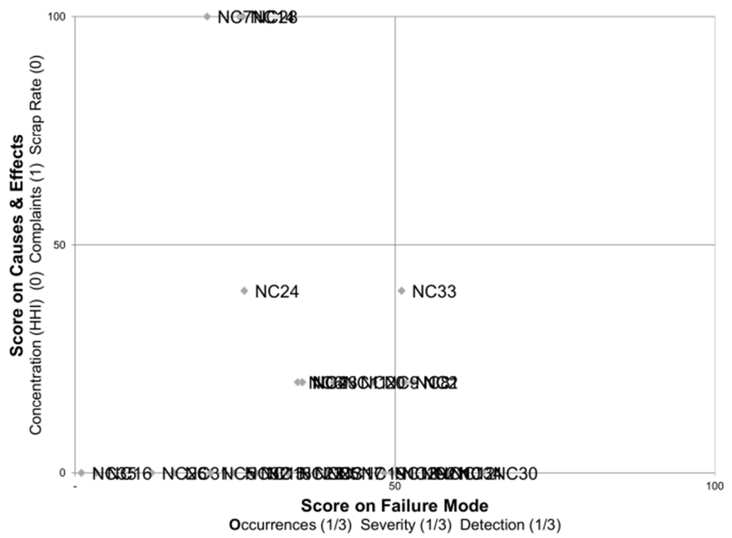


Figure 35: Matrix result: All axes with average weights at x-axis and full weight to Complaints at y-axis.

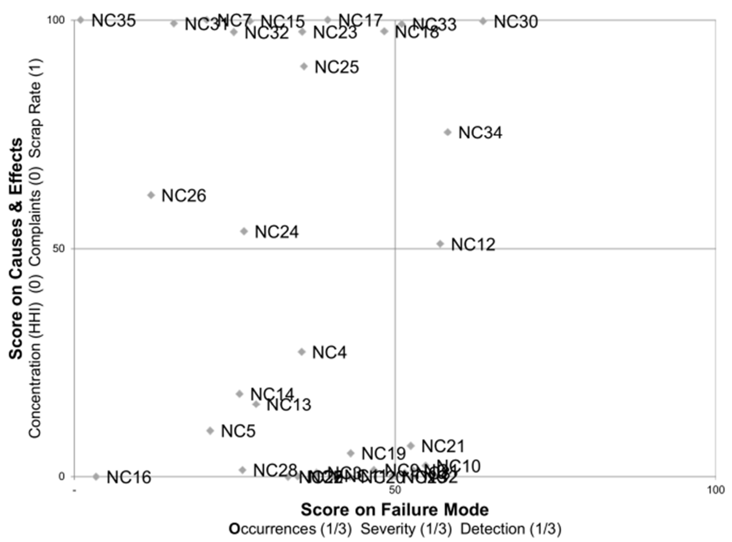


Figure 36: All axes with average weights at x-axis and full weight to Scrap Rate at y-axis.

Figure 34 shows a matrix result with average weights of attributes at the 'risk level' axis and full weight of the concentration attribute of 'causes and effect' axis. By calibrating the weights in that manner one seeks to identify the NCs that are given priority according to the risk level analysis and to the ones which occur concentrated to individual machines. Consequently they do qualify for an efficient investigation of root cause analysis at the corresponding machines. The outcome of this calibration of weights results in identifying two

NCs (NC33 and NC34) in the critical area - the top right quarter. The two “to-be observed” quarters are filled with some NCs but the majority appears in the lower left quarter. Hence priority of further investigation of improving quality should be given to NC33 and NC34. Complementary analysis has to be done to identify root causes and to introduce measurement for improvement.

Figure 35 presents a matrix result with average weights of attributes at the ‘risk level’ axis and full weight of the Complaints attribute of ‘causes and effect’ axis. By calibrating the weights in that manner one seeks to identify the NCs that are given priority according to the risk level analysis and which are complaint about most by customers. Identified NCs would consequently qualify for further root cause analysis and improvement to reduce the number of customer complaints. The outcome of this calibration of weights, results in no identification of NCs in the critical area - the top right quarter. The two “to-be observed” quarters are filled with some NCs but the great majority appears in the lower left quarter. Hence, no immediate priority of further investigation of improving quality can be identified in this calibration of weights.

Figure 36 presents a matrix result with average weights of attributes at the ‘risk level’ axis and full weight of the Scrap Rate attribute of ‘causes and effect’ axis. By calibrating the weights in that manner one seeks to identify the NCs that are given priority according to the risk level analysis and which have a high scrap rate. Eliminating the root causes of those NCs in following improvement projects would reduce the number of scrap, which entails an increase of profit through additional generated sales and reduced failure costs. The outcome of this calibration of weights results in identifying four NCs in the critical area - priority of further investigation should be given to NC 12, NC30, NC 33 and NC34. The two “to-be observed” quarters are filled with some NCs but the majority appears in the lower left quarter.

3.2.3.4.5.2 Maximum Weighting of Two Attributes:

After retrieving results as described in the previous section the second step allocates maximum weights to one attribute of each ordinate axis. The attribute at the ‘risk level’ axis – Severity - is held steady while results are generated by altering the maximum weight setting among each one of the three attributes at the ‘causes and impacts’ axis. Results of the matrices are portrayed in Figure 37, Figure 38 and Figure 39

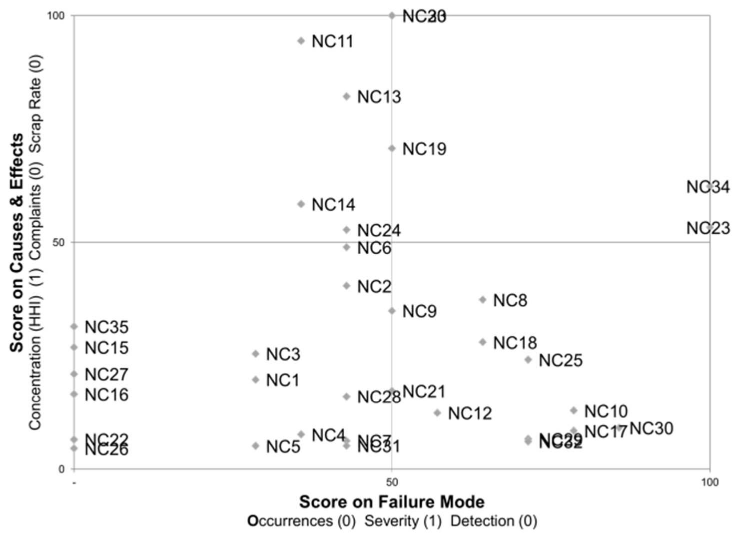


Figure 37: Matrix result: Maximum weights of x-axis attribute Severity and y-axis Concentration.

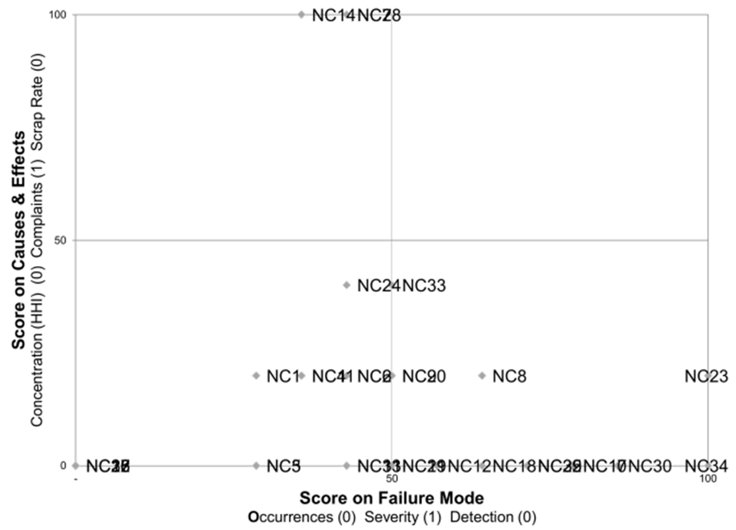


Figure 38: Matrix result: Maximum weights of x-axis attribute Severity and y-axis Complaints.

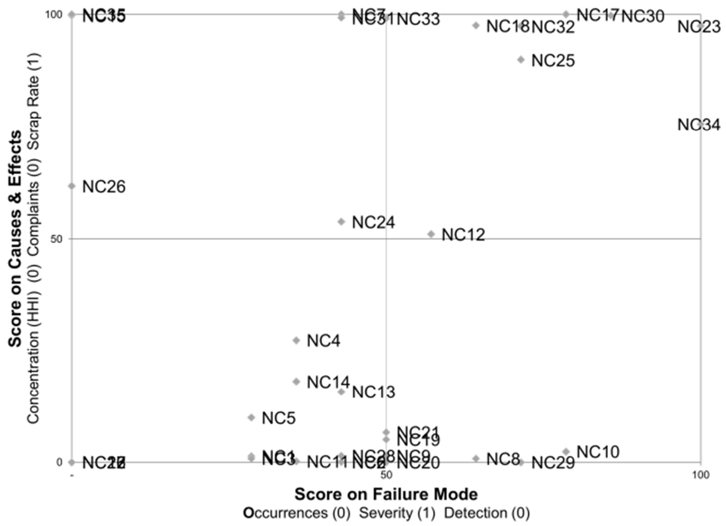


Figure 39: Matrix result: Maximum weights of x-axis attribute Severity and y-axis Scrap Rate.

The calibration of maximum weight setting to severity and concentration is depicted in Figure 37. The severe NCs that occur highly concentrated to individual production machines are identified. By focusing on the prioritized ones and identifying eliminating root causes one can reduce the number of occurrences of severe NCs, which reduces the risk of delivering undetected severe NCs to customers. The outcome of this weight calibration, results in identifying five NCs in the critical area - the top right quarter to which priority of further investigation should be given (NC 19, NC20, NC 23, NC33 and NC34).

The calibration of maximum weight setting to severity and complaints is portrayed in Figure 38. The severe NCs, about which customers complain a lot, are identified. Focusing on the prioritized ones and identifying eliminating root causes one can reduce the number of severe NCs, with high customer complaints. The outcome of this weight calibration, results the identification of no NC in the critical area - the top right quarter. Hence, no immediate priority to specific NCs of further investigation of improving quality identified in this calibration of weights needs to be given.

The outcome of the calibration of maximum weight setting to severity and scrap rate is presented in Figure 39. The severe NCs that are scrapped on a high number are identified. Focusing on the prioritized ones and eliminating root causes can contribute to the reduction of the number of severe NCs, which are highly scrapped. The identified NCs, to which priority of further investigation of improving quality should be given, are NC 12, NC 17, NC 18, NC23, NC 25, NC30, NC32, NC33 and NC34.

In addition to the identified NCs located in the critical area of Figure 34 to Figure 39 other NCs may qualify for further selection as well. If resources are available, NCs in the to-be observed areas (lower right and upper left corner) can be selected additionally for further investigation and improvement.

Table 18 summarizes the NCs found in the critical areas of the graphs from Figure 34 to Figure 39. For each strategy with its corresponding setting of weights of attributes the NC type found in the critical area is listed.

Table 18: NCs in critical area based on strategy for retrieving information.

	NC																																		
Strategy	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**
1a																																	x	x	
1b																																			
1c												x																		x			x	x	
2a																			x	x			x										x	x	
2b																																			
2c												x					x	x					x		x					x		x	x	x	
sum	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	1	1	1	1	0	0	2	0	1	0	0	0	0	2	0	1	4	4	0

The application examples allowed seeing that in a structured manner critical NCs can be identified upon weighted multi-attributes and prioritized for being selected for future improvement projects. The different strategies for setting weights may lead to different prioritization results. If the user is determined about setting the weight the result is explicit. If not, different weighting strategies should be applied and results analyzed to foster the informed decision making.

For example, one possible strategy can be to select the NCs that are prevalently prioritized by the different strategies of setting weights. In this application case these are, according to Table 18, NC 33 and NC 34.

3.2.3.4.6 Complementing Presentation of NC Profile Figures

In addition to the result presentation in the form of matrices a complementing analysis for some selected NCs is suggested. This is done by firstly, defining generic profiles of NCs in shapes and interpreting what the shape denotes. Secondly, the real NC shape profiles are compared with the generic shape profiles. With the proposed visualization it is possible to immediately understand the overall performance of an NC according the different attributes.

Some generic profiles of NCs are depicted in Figure 40. Each figure presents the six attributes from the application case in section 3.2.3.4.1 in the shape of a hexagon. Each attribute is allocated at one corner of the hexagon and the range of the rating is scaled between zero and one hundred with zero being the lowest and originating from the center. The author assumes that NCs with different values in each attribute will result in different shapes. From those shapes it is possible to accumulate information about the profile of the NCs.

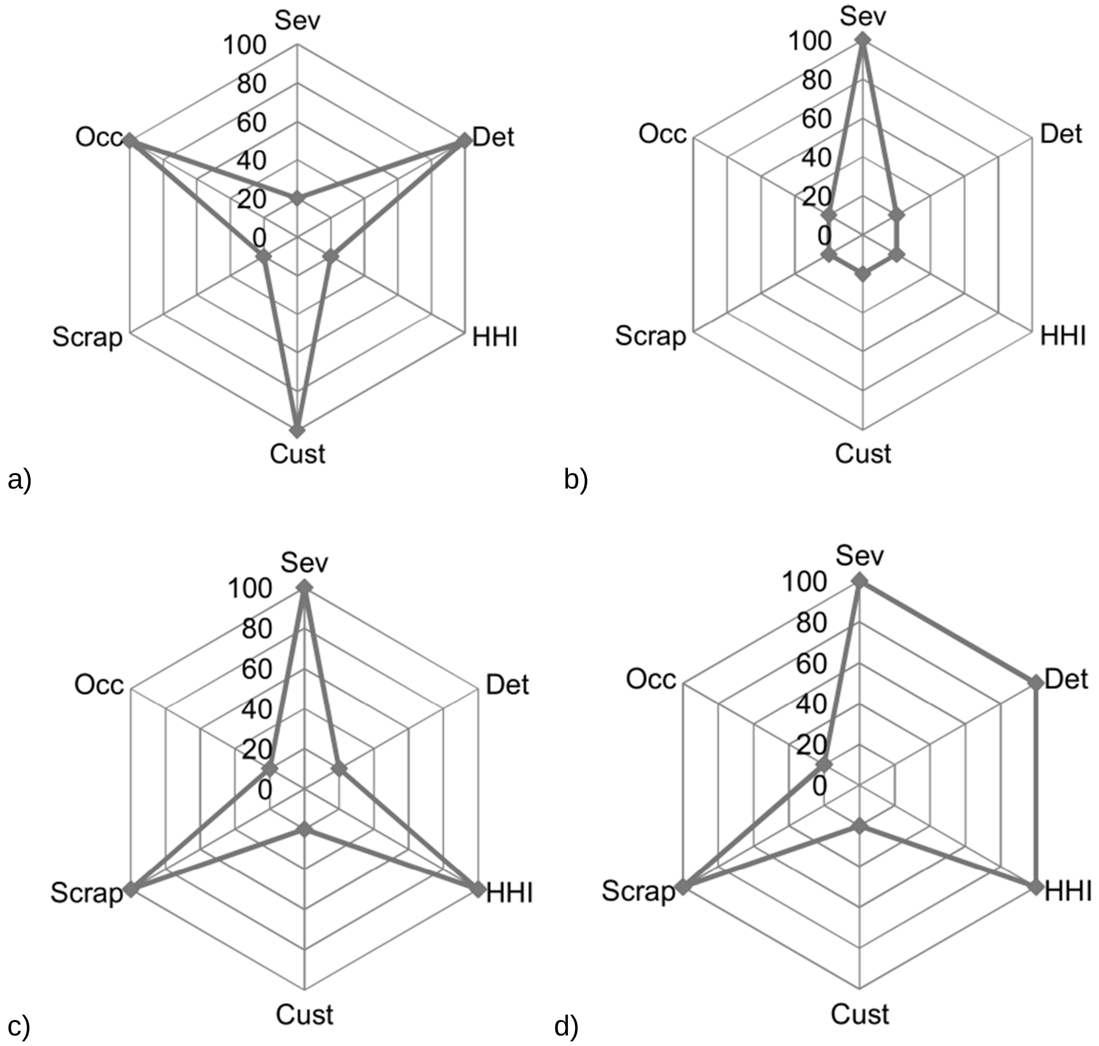


Figure 40: Typification of NCs profiles. a) High occurrence, high customer complaints and poor detection efficiency; b) High severity and low score on all remaining attribute and great detection rate c) high severity, highly concentrated, high scrap rate and great detection rate with low score on all other attributes; d) High Severity, poor detection, highly concentrated and high scrap rate

The shape in Figure 40 a) with maximum values at the attributes occurrence, detection and customer complaints is similar to a three spike star shape. An NC of this shape occurs frequently, is very hard to detect and customers do complain about it. The NC occurs not very concentrated which makes it difficult to identify the root cause at single machines. Fortunately the NC is not sever and a possible threat for customers. The scrap rate is low, which makes the NC recoverable without high scrapping expenses.

The shape in Figure 40 b) has a maximum value of the attribute Severity. An NC of that shape is very severe but easily detectable. In addition to that it rarely occurs and is not very concentrated to individual machines. Thus, there are only few complaints due to low occurrence and a sound detection.

An NC profile of the shape in Figure 40 c) is very severe, hardly detectable and occurs rarely. Scrap rate is high and the NC occurs very concentrated at individual machines with few customer complaints. There is a high incentive to improve quality of an NC with such a profile because improvement reduces scrap, which is directly correlated to an improvement in profit. Furthermore, the NC occurs very concentrated to individual machines and the root cause may be identified quickly.

An NC with the shape of Figure 40 d) is very severe and barely detectable. It rarely occurs and is very concentrated to individual machines. Every time it is detected it is scrapped. Fortunately complaints are low but the potential image loss of an undetected NC at the customer is beyond price. The root cause of an NC of this profile may be easily to be identified at individual machines. Reducing scrap is rewarded with profit improvement. Another benefit is reducing the likelihood of delivering severe NCs to customers.

After setting some generic NC profiles one can match the shapes with all identified NCs to quickly identify NCs with such profiles. NCs are detected that match a generic profile as one can see in Figure 41 and Figure 42. The shape mostly matches with the one outlined in Figure 40 c and the interpretation can be done as previously described.

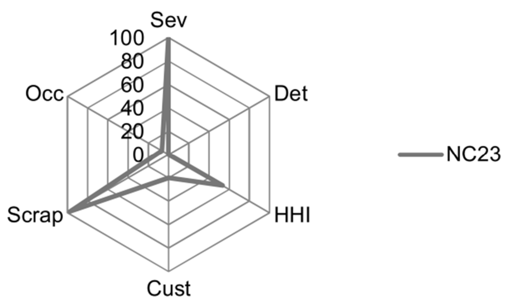


Figure 41: Shape profile of NC 23.

Figure 42 a and Figure 42 b depict the shape profile of NC 33 and NC 34, which are also the NCs prevalently identified by the strategies in section 3.2.3.4.5.1 and 3.2.3.4.5.2. The shapes have similarities with the generic profile shape of Figure 40 d). While NC 33 is less severe it is barely detectable and customer complaints are captured. It has a very low frequency of occurrences but appears very concentrated to single machines. Every time it does appear it is scrapped. NC34 is very severe but detectable. It appears very rarely, not as concentrated as NC 33 and is occasionally recoverable instead of being scrapped.

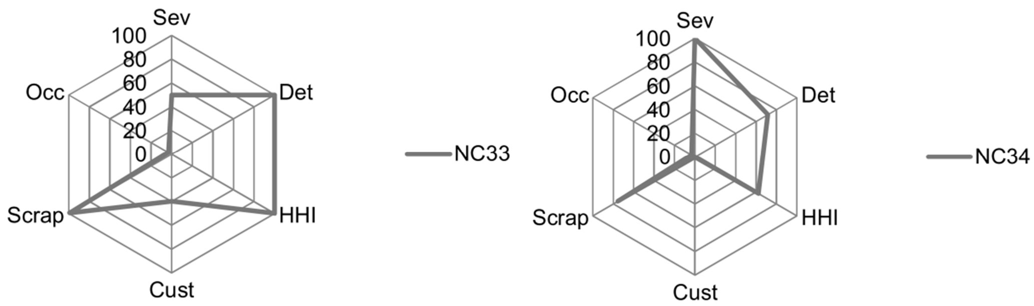


Figure 42: 15 a) Shape profile of NC 33; b) shape profile of NC 34.

3.2.3.5 Remarks

On the path of striving for increasing customer satisfaction TQM is a versatile companion. Successfully proven tools and techniques are great levers to improve quality. But different industries with different products and processes are of different natures targeted to serve different customer needs. Thus, generic tools and techniques do often not cope and new solutions must be tailored. This is especially true for a complex product in mass production with high customer needs, massive data availability and 100% final inspection. If the nonconforming quality level is composed of numerous individual nonconformities it is of importance to identify the most critical ones for future improvement projects.

The approach can be viewed as a quality tool and is a contribution to the field of TQM. It is targeted to the audience of researchers and practitioners in quality management. The approach serves a clear function: prioritizing NCs by selective tracking to identify the most interesting ones for future improvement projects. Strong points of the method are its great visualization and modular composition of attributes. The 2x2 matrix eases the presentation of results for highlighting the importance and for engaging management in order to set basis of a successful improvement project. The approach is highly flexible because the priorities given can be changed to retrieve different results. Furthermore, the multi-attributes on each axis can be easily composed differently if more attributes are identified as relevant or existing ones assessed to not be contributing anymore.

Future research could be directed towards identifying the validity of the approach in different environments other than the one described in the application case of this approach. Additionally, improving the effectiveness of the approach from the perspective of the user can be investigated. For instance one must consider updating the input of attributes or redoing the evaluation of qualitative data over time. Also worth considering is the integration to the IT system of a company to comfortably treat and input quantitative data.

3.3 Simulation Model

The previous subsections analyzed quantitatively and qualitatively the manufacturing processes at the inspection station. Additionally, a study on possible root cause analysis and the prioritization of NCs was given. This section deals about analyzing the dynamic behavior of the system based on its variable nature that was discovered in the previous sections. In order to consider the variable behavior of a system a discrete event simulation (DES) model was generated. Due to the highly illustrative characteristic of simulation models it is a suitable tool to communicate manufacturing process analysis with management.

The following three sub-chapters are structured as follows: First a description of the simulation system is presented, which represents the real inspection system that is illustrated in Figure 15. This is followed by two analysis of the inspection system.

3.3.1 Simulation Model Description

In order to analyze in detail the manual visual inspection system upon quantitative and qualitative aspects a discrete event simulation (DES) model was created. Quantitative aspects analyze the capacity of the installed buffer of the inspection system and reveals bottleneck situation along the day during shift changes and breaks. Qualitative aspects deal with the effectiveness of the product appraisal at the inspection system to quantify delivered nonconforming products. The effectiveness of the product appraisal is done upon one generic product with variability of the inspection system.

Carson II (2004) [112] describes the steps of a sound simulation study, which are followed in this research: (1) Problem Formulation and Setting of Objectives (2) Overall Project Plan (3) Conceptual Model and Assumptions Document (4) Model Development (5) Data collection, cleansing and analysis (6) Model verification and validation (7) Experimentation, Analysis and Reporting.

At the beginning the problem is formulated and the objectives of what information the simulation system should provide were set. The steps to build the simulation system are integrated in the overall project plan. After the conceptual model is devised, as one can see in Figure 15, the model was developed. The data collection took place through observation, expert interviews (managers, engineers and operators), measurements and data retrieval from the IT system. Expert group meetings were conducted in order to firstly verify the simulation model and to secondly validate jointly the input data, layout and conditions. Participants from the departments of industrial engineering, production, engineering, innovation and the quality department were present. The following data was verified and validated:

- Shift schedule of operators (including small breaks and lunch break)
- Allocation of workforce
- Conveyor capacity and velocity
- Conveyor distribution system and allocation logic to feed visual inspection stations
- Quality of product assessment according to individual NCs

The simulation model takes into account the real inspection system as described in Figure 15 and its visualization is depicted in Figure 43. As one can see the simulation model orientates itself closely to the detailed process mapping in Figure 15. There are 24 inspection stations equipped with individual buffer stations. A circular conveyor operates as a buffer system in case the individual inspection stations buffer limits are exceeded. Also three feeding conveyors are considered. Hereby, the simulation takes into account the real dimensions and velocity of the conveyor system. Moreover, product dimension, feeding rhythm, and priority and allocation rules are taken into account.

To each operator at the visual inspection stations performance parameters can be individually allocated. This means each operator can operate with an individual process rate (cycle mean time and standard deviation) to inspect the product. Likewise is the inspection error rate individually attributable, which allows having some operators be qualified to inspect more precisely the products upon conformance or nonconformance. The simulation model includes a grading station and a rework area.

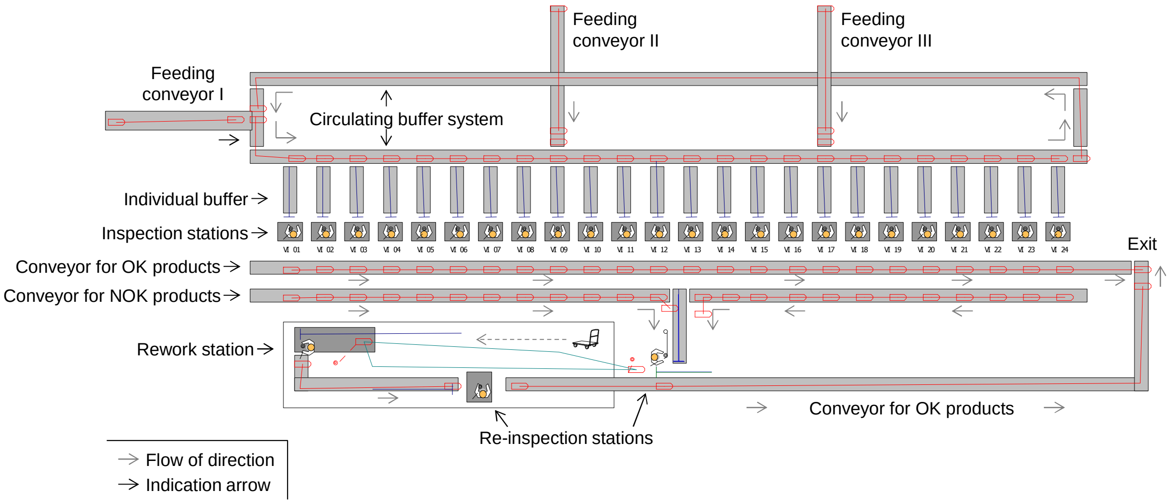


Figure 43: Visualization of the simulation model.

While Figure 43 presents the visualization of the simulation model Figure 44 depicts its logic. The parameters of the simulation model and the decision to be taken at certain ramifications are shown.

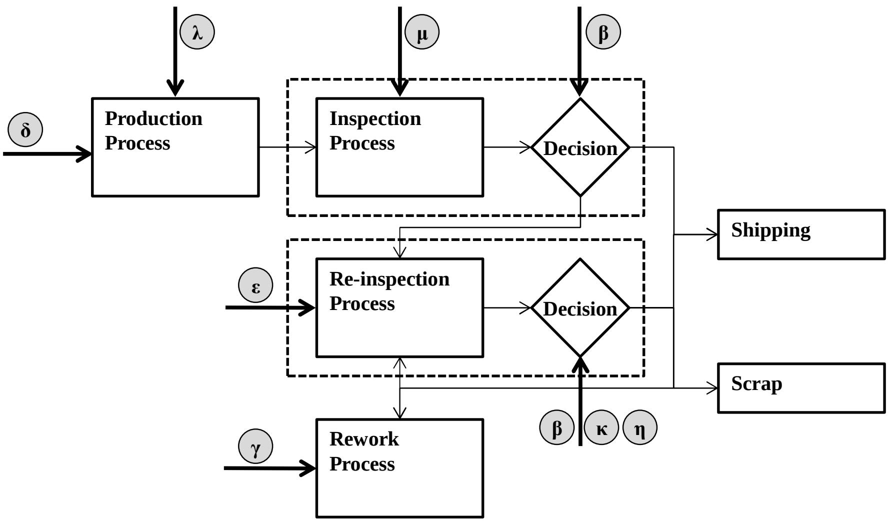


Figure 44: Logic of the simulation model.

The simulation model's symbols are listed in Table 19.

Table 19: Table of Symbols of simulation model.

Symbol	Name	Symbol	Name
λ	Production rate	ε	Re-inspection process rate
δ	Probability of conforming item $\delta \in [0,1]$	γ	Rework process rate
$1-\delta$	Probability of nonconforming item	κ	Probability of conforming re-inspected item
β_i	Probability of inspection error $\beta \in [0,1]$ $i = 1,\dots,n$	η	Probability of non-conforming re-inspected item
μ_i	Inspection process rate	$1-\kappa-\eta$	Probability of scrap item; $\kappa + \eta \leq 1$

The inputs of the system are entities that epitomize a product. Each entity can be loaded with attributes. In addition global variables can be defined. Kelton et al. [113] describe variables and attributes in simulation as follows: Variables are user defined global data storage objects used to store and modify state information at run initialization. They are visible everywhere in the model. Attributes are local data storage associated to entities. Unlike variables, which are global, attributes are local at entities in the sense that each instance of an entity has its own copy of attributes. Attributes are attached to an entity and can be regarded as a characteristic or feature.

The creation of the entity happens according the variable λ, which determines the production rate. Each process – inspection, re-inspection and rework – has its own variable (μ, ε and γ) that determines the process rate. The rates such as production or process rates can be associated with distributions to include the variable nature of the real system. These rates can be allocated to resources such as production machines or operators for instance.

The attributes of the system are related to the entity/product quality. They could also comprise other aspects such as geometrics, color, etc. At its creation the entities' attribute is charged and can be conforming with probability δ or nonconforming with probability $1-\delta$. Different types of Nonconformities can be modeled according to occurrences at the real inspection system. The inspection system is manually performed and the product assessment can be imperfect. Thus, inspection errors must be considered since conforming products can be rejected and nonconforming products accepted. The inspection error is considered as β.

Running scenarios to understand the behavior of a complex dynamic system is possible based on all the presented variables. A scenario analysis includes simulation runs with the alteration of values for variables. The results in the form of process data must be analyzed before conclusions can be drawn.

3.3.2 Analysis of the Effectiveness of the Inspection

This section analyses the effectiveness of product appraisal at the inspection system. The analysis is done based on the simulation model, which follows the described logic in Figure 44 and is illustrated in Figure 43.

3.3.2.1 Scope of the Analysis and Methodology

The scope of this analysis is to analyze quality costs by means of simulation. In particular the effects on quality costs by the adoption of soft TQM elements are analyzed by means of DES. The soft TQM elements, as presented in Table 3 are 'continuous improvement' to improve manufacturing processes and investments in 'knowledge and education' to enhance the effectiveness of the inspection process.

Figure 45 presents the methodology to understand the effects on quality costs by adopting soft TQM tools. Quality costs comprise the PAF-method as described in 2.2.2.1. Soft TQM tools refer to the ones listed in Table 3.

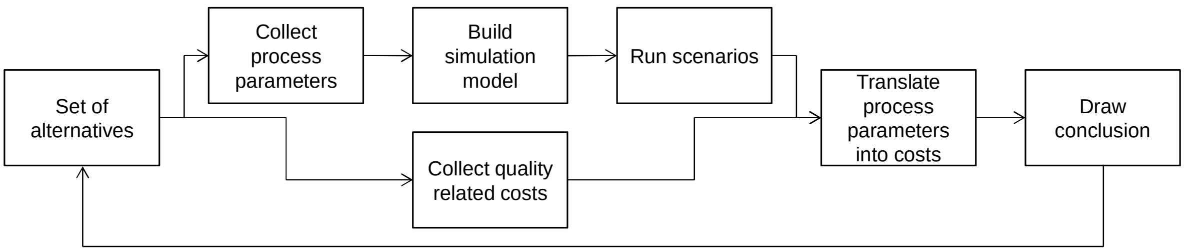


Figure 45: Methodology to understand the effects on quality costs by adopting soft TQM elements.

At the beginning the alternatives were set and relevant process parameters for the manufacturing system were collected. Next the simulation model was built and validated and scenarios run. In parallel to the aforesaid, quality related costs were gathered (details to the gathering process can be found in section 2.2.1). The output of the simulation runs in terms of new process parameters needed to be translated into costs and conclusions could be drawn. Based on the conclusions alterations of the actual manufacturing system can be made. After observing the altered system and identifying new alternatives the presented methodology can be restarted again.

For this analysis a NOK ratio of 9% is assumed, which is in conformance with measured data (please refer to Figure 19 in section 3.1.2). This means that 91% of the data is conforming and 9% items are nonconforming. These values are used as probabilities for the product generation process. With $q_1 = 0.91$ the generated product is conforming and with $q_2 = 0.09$ the product is nonconforming, which is attributed to δ in the model's logic presented in Figure 44.

Human processes are fallible hence the simulation model takes into account type I and type II errors. It is generally understood that rejecting conforming items at the product appraisal is a type I error and an accepting nonconforming items a type II error. Type I error contributes to unnecessary re-inspection and type II error is an undetected delivered nonconformity that may return as a customer claim.

In this study the inspectors are grouped in different categories. Each category presents a representative type of inspector with characteristics of performances such as inspection cycle times or inspection errors. Inspection errors vary as displayed in Table 20. If β is the inspection error then $1 - \beta$ is the probability of making a correct decision. In addition to that also the inspection cycle time varies among the operators. According to best fit analysis of measures from Table 9 the assumed distribution of product inspection can be described as a lognormal distribution. The lognormal distribution is assumed for every operator with different mean inspection times and deviations. The inspectors can be categorized by their performance, the velocity of inspecting an item, and their error rate, the probability of committing a type I or type II error. For simplicity reasons there are twelve categories defined to describe an operator performance. The categories are defined by the two branches performance and fallibility as shown in Table 20. Thus, each category has a distinct combination of cycle time and inspection error. In order to distribute the performances and error rates to the 24 operators at the visual inspection station in the simulation one category is assigned to two operators.

Table 20: Performance and fallibility of inspection operators with $(\boldsymbol{\beta_1 < \beta_2 < \beta_3 < \beta_4})$.

inspection rate	Inspection error (type I and II)			
	β_1	**β_2**	**β_3**	**β_4**
μ_1	$\mu_1\ \beta_1$	$\mu_1\ \beta_2$	$\mu_1\ \beta_3$	$\mu_1\ \beta_4$
μ_2	$\mu_2\ \beta_1$	$\mu_2\ \beta_2$	$\mu_2\ \beta_3$	$\mu_2\ \beta_4$
μ_3	$\mu_3\ \beta_1$	$\mu_3\ \beta_2$	$\mu_3\ \beta_3$	$\mu_3\ \beta_4$

3.3.2.2 Results of the Study

In order to analyze the financial impact firstly a base case scenario is created with the corresponding process parameters in the simulation model of Figure 44. By modifying the parameters and running the different scenarios the resulting process parameters can be translated into cost. Thus, the cost behavior of the different scenarios can be analyzed.

In the presented study the financial effects of selected Soft TQM tools, as presented in Table 3, is measured. The selected strategies are 'continuous improvement' and investments in 'knowledge and education' to enhance the reliability of the inspection process.

Figure 46 illustrates the financial impact of soft TQM tools on quality costs. Cost trends of prevention (P), Appraisal (A) and Failure (F) are depicted. Continuous improvement leads to an increased quality level, which represents the percentage of conforming products among all produced products. Enhancement of the inspection leads to an increased reliability of the inspection with less inspection errors.

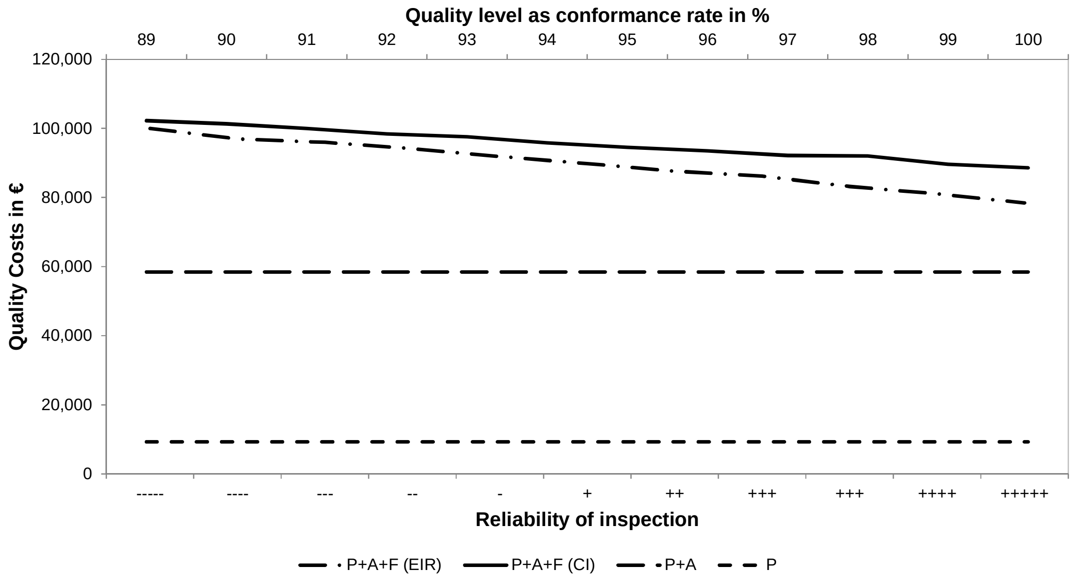
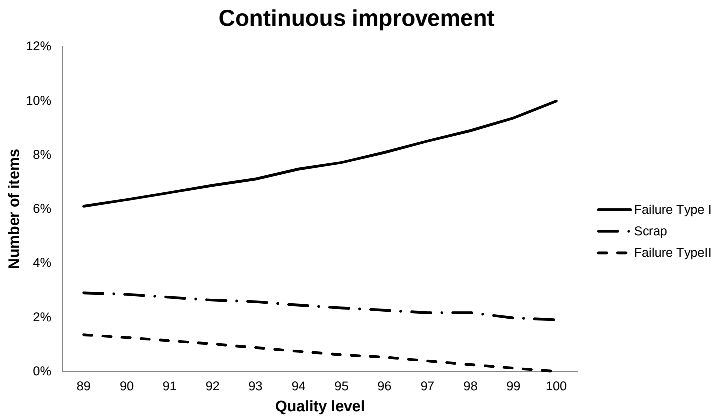


Figure 46: Results of the simulation runs with efforts in continuous improvement and enhancing the inspection reliability

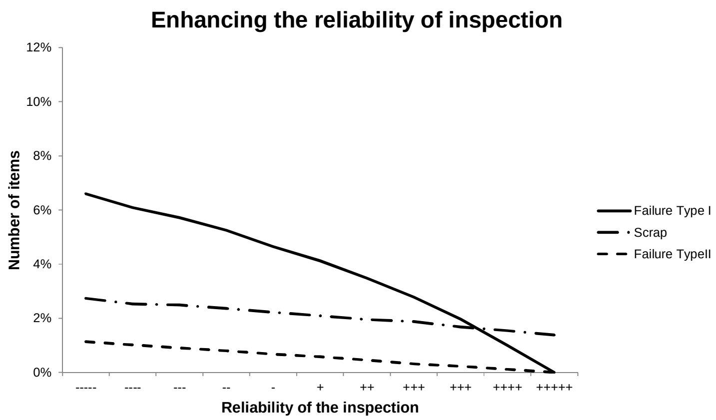
The quality costs refer to a fictive basis of 100.000€ in order to disguise real values of the affiliated company. Investments cost are not taken into account so that Prevention (P) and Appraisal (A) costs remain the same in Figure 46. The decrease of total quality costs is entirely realized by the decrease of Failure (F) costs as improvement takes place. Figure 46 presents two x-axes. The lower one represents the level of inspection reliability and the upper one the quality level. P+A+F (EIR) refers to total quality costs (prevention + appraisal + failure = total quality costs) for the case of an enhancement of the inspection reliability (EIR). P+A+F (CI) refers to the total quality costs in the case of continuous improvement (CI).

Increased reliability is stepwise implemented in the scenarios of the simulation model. This is done by reducing the settings of the inspection errors $\beta_1 > \beta_2 > \beta_3 > \beta_4$ (with β_1 being the least reliable inspector, who commits the most inspection errors, and β_4 being the best inspector, who commits the least inspection errors). The values are incrementally altered, which assumes an improved reliability in the form of $\beta_1 = \beta_2 > \beta_3 > \beta_4$. The final assumption is the best case situation with $\beta_1 = \beta_2 = \beta_3 = \beta_4 = 0$. This is depicted as minuses and pluses in Figure 46 with plusses referring to the latter best case scenario. An Increased quality level is also stepwise implemented by increasing the conformance rate δ.

Figure 47 depicts for both scenarios CI and EIR the trends of scraping and committed failure type I and II.



a)



b)

Figure 47: Comparison of process parameters for a) continuous improvement and b) enhancing the reliability of inspection.

Increasing efforts in continuous improvement will lead to a better quality level eventually, which will decrease the number of nonconformities at manufacturing processes. Therefore the quality level is altered in steps of 1% as shown in Figure 46 on the upper x-axis. In addition Figure 46 shows the effects on quality costs by increasing efforts in continuous improvement. For each percentage of quality improvement around 1% of quality costs are saved up to around 22% of savings for reaching an actual zero defect state. Costs decrease slower compared to enhancing the reliability of the inspection process primarily because failure type I increases by the increased proportion of conforming items as one can see in Figure 47 a. Even when having a theoretical quality level of 100% type I errors are still committed by the inspectors and lead to inefficiencies at the re-inspection and rework area.

Enhanced reliability of the inspection process can be achieved through investments in knowledge and education. This is realized by training and education for operators of the inspection process and will result in reduced type I and II errors as plotted in Figure 47 b. Enhancing the effectiveness of the reliability of the inspection promises higher savings compared to improving the quality level. Relying 100% on the decision of the inspection will be rewarded with up to 11% of savings of total quality costs.

3.3.2.3 Results discussion

This analysis does not take into account investments in order to achieve the improvements as assumed for the investigation. However, as shown in Burgess [62] if the time period (t) is long enough any investments in prevention are justifiable for fulfilling the following inequation. Analogously it shall be viable for appraisal activities.

$$t > \frac{\Delta_{invp}}{\Delta_d * c} \tag{21}$$

With $invp$=investment in prevention activities, d=reduced defect level and c=costs of un-prevented defects.

This methodology has shown positive and quantifiable effects for efforts in prevention and appraisal activities. Although investments are not considered, one can estimate the budget available for investments to spend by critically and realistically evaluating and choosing the quality level or inspection reliability to achieve.

The results of this offline study of production alternatives support the decision maker by turning a decision under incomplete information into one with enriched information. Thus times, efforts and investments for making online changes at the real system can be spent for the monetary more rewarding alternative. Furthermore, the results show that reducing the inspection error has the highest financial benefit which is also described in the findings of de Ruyter et al. [77]. Both options of improvement contribute to the reduction of type II error which is of high importance since the damage of delivering products with nonconformities to the customer is inestimable because of customer losses for future business.

In addition to the mentioned results this study indicates that applying the chosen soft TQM tools have implications on TQM results as mentioned in section 2.2 [20]. Business results are improved by reduced quality costs and lower numbers of nonconformities contribute to less customer claims and a higher customer satisfaction. Furthermore less undetected nonconformities also have a positive impact on society if the product is related to safety.

This model is a good basis for further analysis and improvements on the study. In order to represent better the actual environment one could enrich the study with adding and crossing more parameters for the analysis. Those parameters could be the production mix, various production rates and individual types of NCs and their corresponding reliability of detection at the inspection stage. Analyzing total quality costs on the basis of individual types of NCs will be done in section 5.

Gathering and allocating quality related costs to the PAF categories is one approach that does not allow understanding in detail the cost behavior. However, in this study there is no difference made between variable and fixed costs so savings can be considered as theoretical. In section 4.3 of the next chapter an integrated cost modeling approach of process-based cost-modelling (PBCM) and Time-Driven Activity-Based Costing (TDABC) are presented allowing estimating better the cost components of activities. Combing theses costs with the resulting process parameters of the simulation provides a better basis for drawing conclusion on the cost behavior in more detail.

3.3.3 Analysis of Shift Changes and Lunch Breaks

In this section the effect of variability of a 100% human based inspection process embedded in between two automated process steps is analyzed. In particular, shift changes scenarios and lunch breaks are analyzed. The analysis relates to the affiliated company.

After presenting the scope of the analysis an analytical approach to understand the inspection system is presented. Motivated by a mismatch of analytic results with observations of the real systems the simulation model logic of Figure 44 is adapted. Scenario analysis for two periods of the day is performed to understand the conditions when bottleneck situations occur. One period of the day is the shift change and the other during lunch breaks.

3.3.3.1 Scope of the Analysis

The scope of the analysis is to understand the effect of human variability in between two automated processes (process step 2 and Exit) in the manufacturing line, as illustrated in the production process scheme (Figure 14).

As already demonstrated in Figure 17 the product inspection times vary significantly. Although daily total production rate varies along the day it follows a rather constant pace. Thus, a mismatch may cause bottleneck situations. In addition to the previously described variability of the human inspection system, observations at the manufacturing plant have shown other sources of variability as well. These are organizational issues such as personnel arriving late to shifts, leaving prior to shift end and extending breaks. These additional sources result in more variability, which is referred to as abnormal variability in the following.

3.3.3.2 Understanding the Inspection System with Analytical Methods

Since the manual inspection system is fed with products from an automated process (rather constant arrival rates), one can think of the system as an expandable process step. If the conveyor at the manufacturing line between the process steps has reached its limitation products start accumulating. If the limit of the accumulation system is exceeded the manufacturing line is blocked. Remedies are either extracting products from the conveyors or increasing the process rate at the blocking production step.

Considering Figure 48 three states of the system can be described as follows:

$\lambda = arrival\ rate\ at\ of\ products\ and\ \mu = process\ rate\ of\ manual\ process$

$\lambda < \mu$ Decreasing buffer between the process steps until buffer is empty

$\lambda = \mu$ Stable buffer

$\lambda > \mu$ Accumulating products in buffer until capacity maximum is reached

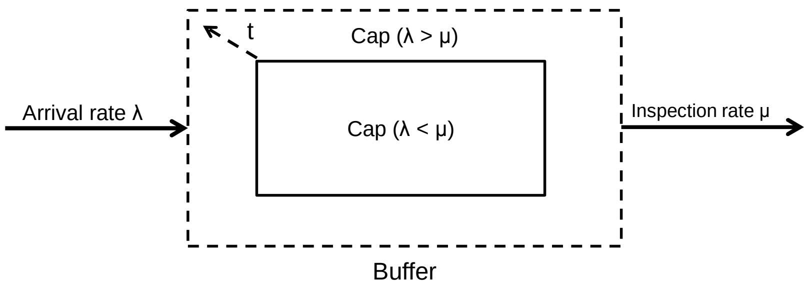


Figure 48: Process step with installed expanding buffer system.

In order to calculate the product arrival per minute the annual production volume ($V(t)$) of roughly 15,000,000 products, as described in 3.1.2, is placed in the following equation:

$$\lambda = \frac{V(t)}{t} \tag{22}$$

Assuming $t = 336$ days each 24 hours results in $\lambda = 31\,products/minute$.

This leads to an arrival rate of $\frac{1}{\lambda} = \frac{1}{31} = 0.0322\ minutes/product$.

For matching this specific rate one need to solve the following equation:

$$\frac{1}{\lambda} = \frac{1}{(\mu * x)} = \frac{1}{\left(\frac{1}{t_{insp}} * x\right)} \tag{23}$$

By solving the before stated equation one matches the arrival rate (λ) with service rate (μ) in order to identify the number of operators needed (x). For the service rate μ the average inspection time determined in 3.1.3 is assumed. With $\lambda = 31$ and $t_{insp} = 31.05\ seconds$ there is a need of 16 operators being constantly placed at the inspection system.

As mentioned before, the real system includes 24 operators for the visual inspection process with an average inspection time of 31.05 seconds. This information paired with the above presented equations indicate a scenario of overcapacity ($\lambda < \mu$). Overcapacity implies a decreasing buffer until empty. However, managers at the company complained about exceeding buffers and blockages of manufacturing processes.

In order to better analyze the systems behavior one must understand the lunch break schedule. All operators are divided in 3 groups. When breaks are needed (for lunch and other smaller interruptions), the shift is organized in a way that only one group of operators can break. This means that for certain periods of the day the capacity is reduced by one third. In periods in which 24 operators work at the inspection station they process in a period of 10 minutes approximately 463 products (considering the average inspection time). On the other hand, in periods of reduced capacity (16 operators) the inspection processing rate decreases to 309 products in a period of 10 minutes. For simplification, the production rate of the previous production step is assumed to be almost invariable at a rate of 313 produced products in a 10 minute time period. In periods of 24 operators working, the exceeding capacity is 48%, while in other periods with less operators there is an under capacity.

According to shift plans operators break for 10 minutes every hour in addition to a 40 minutes lunch break. Eight operators are assigned to three groups, in which the breaks are performed sequentially. Hence, one can identify every hour a period of 30 minutes with a reduced service rate of 16 operators and during lunch of 180 minutes. Even in this reduced capacity conditions, the capacity (16 operators) should be sufficient according to analytical calculations. Theoretically the system seems to be stable but in practice products are exceeding the buffer at some times along the day.

In these analytical calculations, the inspection time is assumed to be constant at its average value (31.05 seconds). Even though, observations and data collection clearly demonstrate that this is not the case, as demonstrated in 3.1.3.2. For this reason, the same calculations were done for an average inspection time 10% higher (34 seconds). In this situation the exceeding capacity with 24 operators is 35%, while in periods with reduced capacity the production rate is 10% below of the previous process. Small and realistic differences in inspection times raise the question whether or not the installed buffer is capable of accumulating products in periods with lower capacity. A closer analysis was done to understand the frequency and distribution of those periods.

Figure 49 depicts produced products and the available capacity at the inspection station during one eight hour shift. Along 480 minutes all regular and scheduled breaks with reduced capacity account for 50 % of the available shift time period. This means that for 240 minutes, the number of operators available is 16. Summarized one can say that in half of the time of a shift the exceeding capacity is 35%, while in the other half the capacity of manual inspection is 10% below the production volume. Having this distribution in mind, the number of products that the operators could inspect during one shift is 16,800. However, along the same period, the inspection accounts only for 14,880 units. Moreover, even with a capacity margin of 13%, there are periods in which the buffer is observed to be completely full and products have to be collected to a tank to avoid blocked production machines.

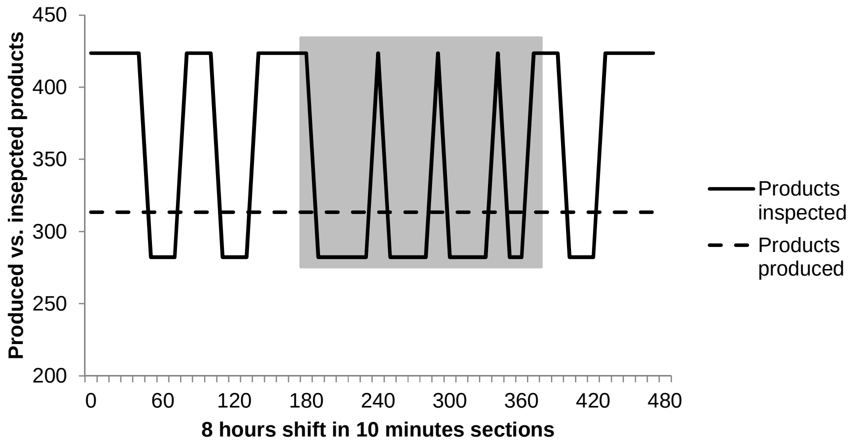


Figure 49: Variation of produced and inspected products along an eight hours shift.

A critical period becomes apparent when taking a closer look at Figure 49 (highlighted in grey). During the interval 180 minutes after shift start until minute 360 (in a shift with the start at 8 am is equivalent to the period between 11am to 2pm), the final inspection is performed with a reduced capacity of 150 minutes out of 180 minutes.

In addition to the previously described reduction of capacity two other important factors must be mention but are neglected in this analytical model for simplification purposes. Additional contributors to buffer blockages are late arrival of some operators and the natural variability of operators' inspection times. In these analytical calculations, the inspection time was assumed to be constant.

These analytical calculations revealed that the nominal capacity installed exceeds the needed capacity. In fact, the plant's observations showed that there are moments along the shift in which the operators are idly waiting for products to arrive. And in other moments the installed capacity is not enough to inspect all products and the buffer in between is completely full. While these analytical calculations are a good indicator of the state there is a need to analyze this situation more closely to reality.

For this reason the simulation model of Figure 43 and Figure 44 was adapted to take into account the variability in inspection times, shift schedules and temporary absences (breaks, lunch, etc.). Another aspect that was modeled was the shift change and the effect of late arrival to shift start. Data collected at the plant and observations made, revealed that this is also a critical moment in which there is tendency for buffer blockages to occur.

In order to analyze the system and to identify clearly these situations the simulation model was consulted. By varying the values of the variables a sensitivity analyses was performed.

3.3.3.3 Understanding the Inspection System by Means of Discrete Event Simulation

Figure 50 illustrates an adapted version of the simulation model presented in Figure 44. The new element in the simulation model is the collecting tank linked to the buffer. The buffer serves to absorb products that exceed the capacity of the system. In reality whenever the buffer reaches the capacity limit the production process of the previous automated process is blocked and does only continue when space in the buffer is available again.

In order to measure the effect of a blocked production processes products are extracted to the collecting tank. In this way the opportunity costs of blockages becomes quantifiable in the form of unproduced products and can be calculated. For simplification reasons it is assumed that the automatic process is equipped with sufficient capacity to process products at all times.

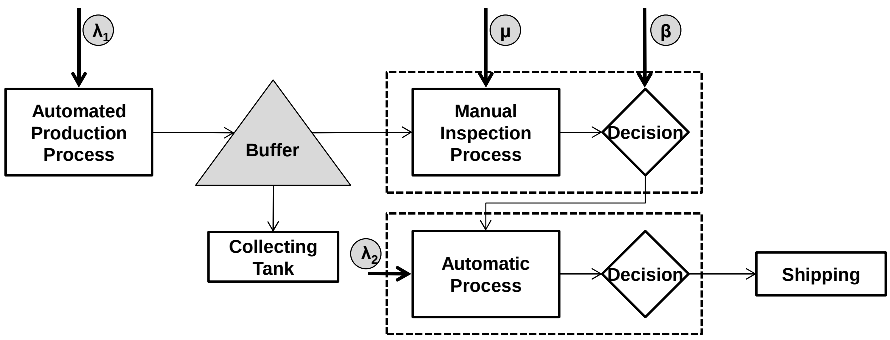


Figure 50: Diagram of the processes involved in the simulation model.

3.3.3.3.1 Shift Change Analysis

After adapting the simulation model and variables as displayed in Figure 50, changes of relevant variables can be done in order to identify the critical situations. Observations and data collected at the shop floor confirmed that shift change is a critical period for the production flow. The fact of leaving prior to shift end late arrival of operators creates disturbances at the manufacturing line. A full operating workforce implies exceeding capacity and the buffer before the manual process absorbs uncertainty regarding workforce number and inspection time. The question to analyze is whether or not the current buffer and/or exceeding capacity is/are enough to deal with periods of transition between shifts.

To analyze in detail the effect of the shift change some variables were kept constant. Those constant variables were production rate and the individual inspection rates along the various simulations. The variables that were placed iteratively with different values for the simulation runs were the time of late arrivals and the number of operators arriving late. Each time a variable was changed the simulation model was run with 10 replications.

Figure 51 illustrates the results obtained for different configurations by varying the number of operators that were temporarily absent and their time of absence. From shop floor observations, situations in which only half of the workforce was in service were common. This is the reason why, a variation between 8 and 16 stations idled was considered.

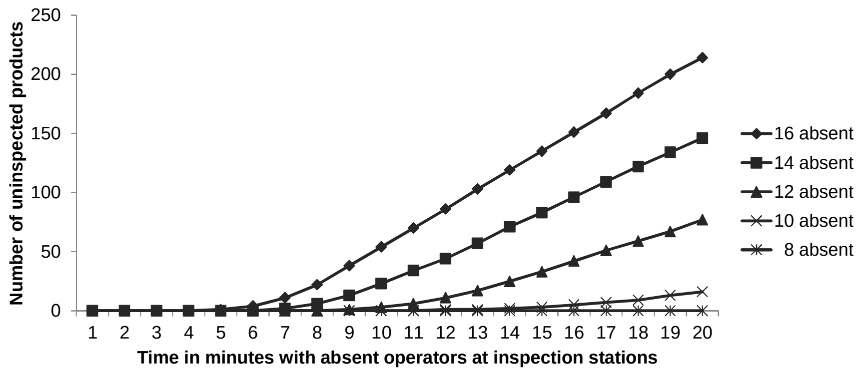


Figure 51: Buffer level as function of the number and time of operators absent.

The results show that for a constant production rate and varying the time needed for the shift change to occur completely (moving from 24 operators to 0 and from 0 to 24 operators), there are some situations in which the buffer in between is not sufficient. The buffer is not capable of absorbing products in case 16 operators are absent for 5 minutes or more. When only 8 stations are idled, the shift change can last up to 20 minutes without blockages. These results tend to be consistent with the analytical calculations. As seen in previous sections, the inspection rate with reduced workforce (16 operators) is not significantly lower than the arrival rate and if the period of such an occurrence is not long the buffer should be able to absorb the variability. Even though, the results point out the need to carefully control the way the shift change occur because small variations in the workforce and time absence can cause blockages. Situations in which only half of the workforce is operating as observed in reality can only occur up to 9 minutes.

3.3.3.3.2 Lunch Break Analysis

To analyze another critical moment (lunch break) a different set of simulation scenarios were run. In this case the simulations corresponded to a complete shift (8 hours), starting without absences (24 operators operating at the beginning of the shift) and defined that after 180 minutes the number of operators was reduced to 16 according to the lunch schedules. The production rate was varied for each simulation set. Results are shown in Figure 52.

Figure 52: Buffer level of unproduced products for different production rates.

Figure 52 shows the accumulation of products that exceeded the buffer capacity as a function of the production rate. In accordance to plant observations, blockages occur during lunch breaks for the current production rate 31.3 products per minute (highlighted in grey). This means the current design of the process has not enough capacity of the current production volume when taking into account the operators' variability at the manual inspection process.

3.3.3.4 Remarks

The simulation model allowed understanding in detail the process flow and the impact of human variability of the inspection system. The installed buffer is of major importance to absorb a certain portion of this variability. The simulation model results confirm the industrial observations that blockages can occur during shift changes and lunch breaks. Moreover, the bottleneck situations during shift change are clearly identified and the incapability of the current process revealed.

Expanding the buffer size may not be a desirable solution since any production volume increase would simply delay blockages. Another alternative would be to adjust the production rate according to the workforce availability (lower production rates in critical periods). In addition, some actions should be done to ensure a more stable and reliable work performance from the human inspection process step. One of the first set of actions implies stricter rules regarding shift changes to minimize the misbehavior of operators (leaving prior to shift end and arrive late). A strategy to do so would be to adopt an hourly productivity bonus, instead of an overall daily productivity bonus. A daily bonus allows the operator to compensate lower production periods along the shift, while an hourly bonus would motivate a more stable output along the day.

To minimize the negative impact of lunch breaks, one suggestion could be to have two groups of operators. One group permanently dedicated to the inspection task and a second group of flexible operators trained to perform inspection tasks during lunch or other breaks.

The simulation was adapted to reflect this adjustment in the workforce. Several iterations were done, and results show that if 18 operators are located permanently at the manual process, there is no blockages for a production rate of 31.3 products per minute (Table 21).

Table 21: Impact of flexible workforce on daily production and blockages.

Arrangement of inspection	Production rate (products per minute)	Daily production volume	Number of operators	Blockage
As-is	31.3	45,000	24	Yes
Flexible workforce	31.3	45,000	18 permanent + 6 flexible	No
Flexible workforce	32.3	46,512	18 permanent +6 flexible	No

Actually the production rate can even be increased to 32.3 products per minute and there would still be a stable process. The shift could be organized as follows: Instead of 24 operators there are 18 operators assigned to the manual inspection process. These 18 operators are divided in 3 groups of 6 each. When one group takes a break, a group of 6 flexible operators assume their position. This way, a permanent number of 18 operators is always guaranteed, which minimizes the probability of blockages. Additionally, this flexible group of operators can be assigned to other tasks when the permanent operators work. This reduces the effect of overcapacity. Not only can the production rate increase, but also a utilization of the flexible operators for other tasks can occur. Each of the 6 flexible operators has 160 minutes per day that can be assigned to other tasks.

3.4 Summary

This chapter presented both a quantitatively and qualitatively assessment of the as-is situation of the affiliated company. Hereby, the performances in terms of cycle times, production volume and product assessment are considered.

In order to perform a more precise analysis two approaches, which can be regarded as quality tools, were developed. Besides being tailor made tools for the affiliated company they present a general approach that can be used in other environments with similar problems [115], [116].

Furthermore, a simulation model served to assess identified problems in detail. The complex and dynamic nature of the company’s real system could be successfully modeled. Scenario analysis, in the form of simulation runs with process parameter variation, is the basis for a thorough analysis. After the analysis improvement recommendations were given [36], [117].

The analysis presented in this chapter was done on a micro level related to the manufacturing processes of the affiliated company. The next chapter, chapter 4, deals about costs. Different approaches of cost modelling are presented, performed and gained insights discussed.

CHAPTER 4

4 Cost Modeling and Cost Analysis

This chapter introduces different approaches to model and analyze costs of manufacturing systems. The approaches are important elements which help solving the research questions in this thesis. Hereby, the different cost modeling techniques serve different analysis purposes and do complement each other. All cost gathering results, cost systems or cost estimations refer to the affiliated company as described in 3.1.

In order to gather quality related costs, firstly, the approach of establishing a Cost of Quality (CoQ) System is applied. This approach analyzes the quality costs of a company and its component elements. It furthermore sets basis to another cost system described in the following. Secondly, the method Time-Driven Activity-Based Costing (TDABC) is presented and the performance of the manufacturing system analyzed. Additionally, improvement options to increase the efficiency of the use of workforce are given. Thirdly, a Process-Based Cost-Model (PBCM) is established that helps understanding different design specifications and process operating conditions on process costs. Lastly, a novel approach of combining TDABC and PBCM is presented. The results of the novel approach are used as input for the analysis in section 5.

4.1 Cost of Quality System

As described in 2.2.2 there are different methods to design a CoQ model. In this study the suggested cost allocation method as described in Campanella [53] is followed. Herein, costs are gathered and allocated to cost categories in which they are further distinguished into cost elements. The cost categories are Feigenbaum's [18] PAF categories (Prevention, Appraisal and Failure). According to literature there is no general approach of the cost gathering exercise and costing systems vary across companies due to the readiness of cost data availability or the subjectivity of cost data allocation [56].

4.1.1 Methodology to Develop a Cost of Quality System

In order to create the CoQ system the steps in Figure 53, as suggested by [53] were followed.

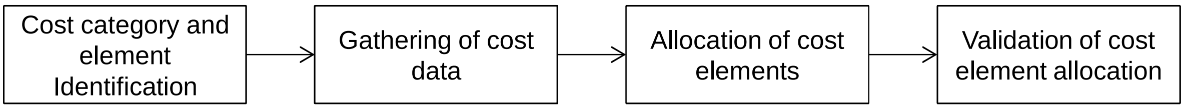


Figure 53: Steps to create a CoQ system according to the PAF allocation approach.

The first step is to identify cost categories and elements. After the execution of the cost gathering exercise cost data is allocated to cost elements. If data cannot be allocated to the cost elements directly, then the application of an algorithm, which can be based on a heuristic, can help. Before the cost system is established the validation of cost elements is a crucial part in the process.

Campanella [53] suggests in detail cost elements of the cost categories Prevention, Appraisal and Failure (Internal and External), which is presented in Appendix III. These cost categories and elements provide a great basis of possible categories. Suitable elements can be chosen, if necessary further elements can be included to the categories. The identification should be done with the knowledge of someone from the accounting and quality department to justify the necessity of the chosen cost categories.

After the identification of cost elements of categories the costs must be gathered from the accounting system or other cost calculation sources. These costs must be allocated to the previous identified cost categories. In cases of doubts an expert opinions can be included.

After the system is established it must be validated with all involved parties. Among those are the responsible partners where the data originated.

4.1.2 Application Case of an Established CoQ System

In this section the previous presented methodology is followed in order to establish a CoQ system for the affiliated company.

Several meetings with the head of the accounting department were conducted in order to identify relevant cost categories and to gather the corresponding cost data. The data provided stems mostly from the company's accounting system but also from spread sheet calculations to estimate and collect indirect cost elements. The collected accounting data is from four different cost centers. Among these cost centers are the quality department itself and departments with cost data akin to quality topics. These are for example departments with field tests of improvement processes or products to avoid imperfections.

The allocation of cost elements was done with a judgment of best fit. Hereby, the gathered costs elements were allocated to the cost categories (Appendix III) suggested by Campanella [53]. In cases of doubt it was necessary to conduct expert interviews and to perform the cost allocation exercise jointly with them. Experts were the head of departments, such as accounting, quality and product industrialization. With each expert the cost allocation process was either jointly done or the detailed approach of the apportionment formula aligned.

Since it is not uncommon to find cost data of the accounting system not readily itemized available an apportionment formula must be tailored. As an example one apportionment formula used considers the distribution of man power allocated to the tasks. While this can be a sufficiently good enough approach it can be more complicated in terms of allocation of machine cost and depreciation. The correctness of the apportionment formula to allocate the cost to the cost elements depends strongly on expert's estimation.

The validation of cost elements was conducted iteratively with experts of where costs were provided from and the head of the accounting department. Hereby, both approaches, the allocation of cost elements to cost categories and the apportionment formulae to distribute costs, were discussed. After the system was established a workshop was conducted with all experts who gave input. In that workshop the methodology, the cost elements, the logic of the distribution and the apportionment formulae were presented as basis for a final validation of the CoQ model.

The result of the final, validated version of the CoQ system is presented in in Table 22.

Table 22: Result of the cost collection and allocation exercise to create the CoQ system.

Prevention	**9%**
Field Trials	4%
Quality Administration	4%
Investment in prevention projects	1%
Appraisal	**40%**
Operations (Manufacturing or Service) Appraisal Costs	1%
Product or Service Quality Audits	0%
Inspection and Test Materials	36%
Laboratory Support	1%
Investments in appraisal projects	1%
Internal Failure	**49%**
Rework	8%
Reinspection/Retest Costs	9%
Scrap Costs (Operations)	28%
Scrap collection	1%
Scrap selection	3%
External Failure	**2%**
Warranty Claims	2%
Sum	**100%**

The established CoQ system presents the total quality costs of the affiliated company. In this way the scrap level, nonconformance rate or other efforts related to quality can be expressed as costs. In that way the individual expenditures for categories become apparent and do serve as a motivation for quality improvement projects.

The largest cost elements of Table 22 account for the categories of Internal Failure (49%) and Appraisal (40%). Expenditure for Appraisal accrues mostly for Inspection and Test Material. Internal Failure is mostly composed of costs incurred through Scrap and Rework and Re-Inspection activities. Hence, there is potential to reduce costs when improving process quality. Improved process quality may lower the need to scrap or rework products and lead to a reduction of internal failure costs. With a better quality level the need of product appraisal might become unnecessary.

External failure is fully composed by ‘warranty claims’ and accounts for 2% of the total quality costs. There is no other data available that can be attributed to the cost elements of the category ‘external failure’ as suggested by Campanella [53] and presented in Appendix I. Most of all the company does not use an approach of estimating lost sales due to product delivery of imperfect quality.

Figure 54 portrays the proportions of the quality cost elements firstly provided in Table 22.

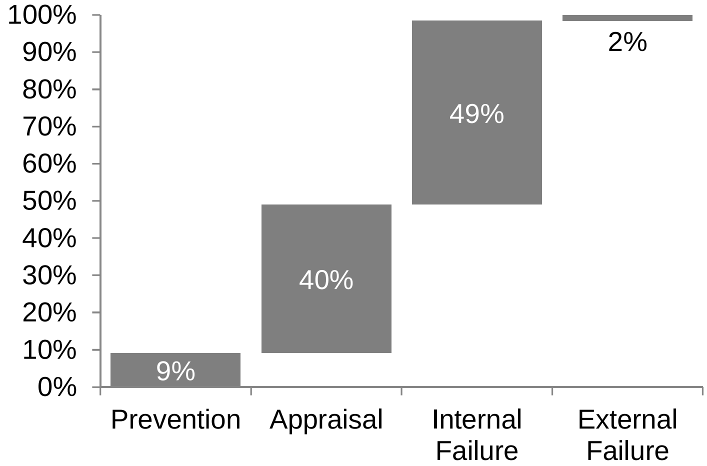


Figure 54: Proportion of quality cost categories of the company under investigation.

Schiffauerova and Thomson [56] assert that company’s most often report CoQ as a percentage of total manufacturing costs. In line with this method of reporting the total quality costs revealed in Table 22 and Figure 54 represent 8% of the total manufacturing costs and 4% of annual turnover.

There is little data published about quality costs in literature. Furthermore, Plunkett and Dale [50] emphasize to be cautious about comparing reported quality costs from different sources. And there are reasons that underline their statement. As mentioned before the methods of gathering quality costs do vary. In addition to varying methods of gathering quality costs also the definition of the cost categories and elements themselves can be different. Also the differing cost systems and data availability to attribute correctly costs to the individual cost elements is questionable.

Although, comparing CoQ costs and elements are discouraged and of limited informational value, one can find the findings in this study fitting in the general reported elements.

However, the findings of Carr and Ponoemon [114] that (1) internal failure is the most expensive quality cost component and that (2) the combination of internal and external failure costs is always higher than prevention and appraisal can be supported. Table 22 and Figure 54 indicates that internal failure epitomizes the highest expenditure in quality costs and the combination of internal and external failure represent 51% of quality costs, which is slightly larger than the prevention together with appraisal of 49%.

Worth mentioning are the external failure costs, which constitute only 2% of total quality cost. However, these do not comprise elements such as ‘quality image loss’, ‘loss of reputation’ or ‘lost opportunity’, such as lost future sales.

4.1.3 Remarks

Establishing a CoQ model demands interdepartmental cooperation regarding the cost gathering and cost allocation exercise. Furthermore, creativity and logic to formulate apportion costs with clear reasoning is necessary. Finally, validation sessions with all involved parties must be conducted to achieve a common agreement and acceptance.

In addition to knowing the proportions of the categories PAF the cost gathering and allocation exercise is the basis of the further cost analysis in the next sections. Based on the previously determined cost elements a further analysis according to the TDABC approach becomes feasible. One can say that establishing a CoQ model provides information about the proportions of the PAF elements and also endorses other cost models.

Although the element ‘lost sales’ is a suggested part of external failure costs (Appendix III) this is rarely an established measure by companies. It is hard to estimate and generally neglected as done by the affiliated company to this thesis.

4.2 Time-Driven Activity-Based Costing

Time-Driven Activity-Based Costing (TDABC) is an adapted method of Activity-Based-Costing (ABC). TDABC allows analyzing the current utilization of given processes. Hereby, overhead or department costs are gathered and all executed activities identified. As a result based on time equations a possible over- or under-utilization of a process becomes apparent. In this thesis the method is used to identify indicators for improvement options.

4.2.1 Methodology to Develop a TDABC System

The approach of Stout and Propri [73] was used to develop the TDABC system (Figure 55).

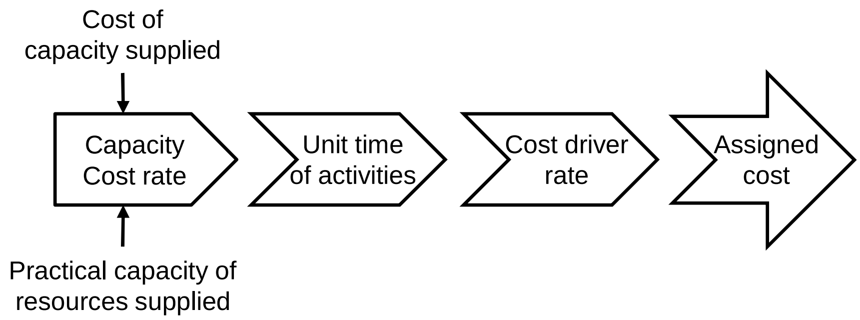


Figure 55: Methodology to create a TDABC system.

In the first step the capacity cost rate of a cost center is calculated, which expresses the monetary value of a time unit for an individual cost center. The second step estimates the times for all performed activities in the respective cost center. The product of the capacity cost rate with each activity identifies the individual cost of performing a specific activity, which is denominated as the cost driver rate. When multiplying the number of each activity with their previously defined costs results in total costs assigned to the cost center. The total costs assigned can be compared to the cost of capacity supplied and the difference indicates over or under capacity.

4.2.1.1 Capacity Cost Rate Calculation for a Cost Center

The capacity cost rate is defined as the division of cost of capacity supplied and the practical capacity of resources supplied. The total cost of capacity supplied (ccs) is the total cost of a department including overhead for a given period. The practical capacity of resources supplied ($pcrs$) is the total aggregated amount of time of all resources employed in a certain department within a given period. Thus, before calculating the capacity cost rate (ccr) the two elements ccs and the $pcrs$ must be determined.

Let ccs_m be the cost of capacity supplied and $pcrs_m$ be the practical capacity of resources supplied of department m then cost of capacity rate ccr_m can be calculated as follows:

$$ccr_m = \frac{ccs_m}{pcrs_m} \tag{24}$$

The practical capacity of resources supplied is the net value of time of the resources being available to perform work. Hereby, one excludes breaks and time dedicated to activities for other cost centers than the one under analysis. It is important that the time periods of determining $pcrs_m$ and ccs_m match. The cost capacity rate (ccr_m) is a value with the unit cost per time.

4.2.1.2 Demand for Resource Capacity Estimation with Time Equations

The second step of developing a TDABC system is to develop time equations. These time equations are determined by the number of activities and the time spent for each of the activities that are performed in the respective cost center. This results in a list of activities with time measures and their respective quantities. Hereby, the time of the performed activity n in cost center m is denoted as ta_{mn} and the number of performed activities as q_{mn}.

4.2.1.3 Determination of Cost Driver Rate and Capacity Utilization

After the basis for TDABC is set with the previous steps the capacity utilization can be determined by joining the information of step one and two. The capacity utilization (CU_m) is simply the difference (or ratio to identify in %) of the sum of estimated cost consumption for all performed activities and the supplied capacity cost ccs_m. The estimated cost consumption of an activity n in department m (ac_{mn}) is determined by the cost of one unit of time (ccr_m) in a given department (m) multiplied by the time consumption to perform that activity (ta_{mn}) and the number of activity executions (q_m) in that respective period. This can be expressed as follows:

$$CU_m = ccs_m - \sum_{1}^{n} ac_{mn} \tag{25}$$

$$with \quad ac_{mn} = cdr_{mn} * q_{mn} = ccr_m * ta_{mn} * q_{mn} \tag{26}$$

Above stated is the cost driver rate (cdr_m), which can be determined through the cost of capacity rate of department m (ccr_m) multiplied by the time of the activity n's duration ta_{mn}.

4.2.2 Application Case of a TDABC System

In order to analyze a case from the affiliated company as presented in 3.1 is presented. Hereby, the formulation of the methodology in 4.2.1 is applied. The basis of determining the ccs are elements of the previously identified CoQ system in 4.1.

4.2.2.1 Setting Up the TDABC System

The analyzed area in this study is a sub division of the cost center final inspection from Figure 14. Thus, the capacity cost supplied of the sub division under analysis is a fraction of the cost center. The basis of cost data that is used as input for the TDABC analysis stems from gathered cost elements as described in 4.1. The analyzed sub division epitomizes a portion of the cost center and is not directly quantifiable. Indirectly estimating the costs by the proportion of the cost elements can be of help. In this case the proportions of allocated workforce were used to estimate and distribute departmental costs to the subdivisions. The overall departmental costs are dividable in the cost elements labor, operational and depreciation costs. In line with equation (27) total cost center costs ($TCCC$) is the sum of its individual sub division costs (SDC).

$$TCCC = \sum_{i=1}^{n} SDC_i \tag{27}$$

With SDC_i being unknown it can be estimated by portions according to their headcount. Be l the total number of people accountable to the cost center then l is the sum of employees of its I sub divisions.

$$l = \sum_{1}^{I} l_i \tag{28}$$

With equations (27) and (28) the sub divisional costs can be estimated by equation (29).

$$SDC_i = TCCC * \frac{l_i}{\sum l_i} \tag{29}$$

With the above presented equation the sub divisional cost of the cost center's area can be estimated and defines cost of capacity supplied (ccs_m from the previous section).

4.2.2.2 Results of the Application Case of a TDABC

Following the steps as described in 4.2.1 results in establishing a TDABC system. In order to determine the ccs_m the estimation approach in 4.2.2.1 is applied and listed in Table 23. To calculate ccs_m and $pcrs$ a yearly basis is assumed.

$$pcrs = DPP * (HPS - PB) \tag{30}$$

In (30) DPP denotes days per period, HPS hours per shift and PB are paid breaks.

Reduced by breaks an operator works 6.67 hours or 400 minutes respectively, out of an 8 hours shift (8 hours / 480 minutes shift reduced by 1.33 hours / 80 minutes of scheduled breaks per shift). Multiplying the 400 minutes with the working days of an operator per year (operators of the company in this application case work 5 days in 48 weeks per year) determines $pcrs_i$ of operator i per year as presented in (31). Thus, $pcrs$ of the department can be calculated by assuming (31) for all available operators as stated in Table 23.

$$pcrs_i = 240 \ * (480 - 80) = 96{,}000 \frac{min}{year} \tag{31}$$

Following the calculations (24) from the previous sections, ccr was determined to be $0.31 \frac{€}{min}$ as listed in the last column of Table 23. This represents the cost of one time unit (minute).

Table 23: Capacity cost supplied, practical capacity of resources supplied to determine capacity cost rate per minute.

Department A	ccs	Operators	pcrs	ccr
Labor costs	3,163,794 €	114.5	10,992,000	0.31 €
Machine costs	117,605 €			
Fix costs (depreciation)	95,804 €			
Total	**3,377,203 €**		**10,992,000**	**0.31 €**

In the next step the activities were identified, listed and their times measured on a sample. Times of activities and their relative number of executions within the sample size are identified. The relative number of executions, the percentages, are used and applied to the entire yearly production volume together with their individual averaged time measurements. Table 24 illustrates the result table to determine total costs according to the TDABC approach. Note that cdr is a result of ccr and the time duration of the activities as explained previously.

The activities listed in Table 24 are the result of a measurement exercise at the inspection station of a period of four days. The first day was merely dedicated to observe and identify the range of activities, which are performed. Having those listed, the activities are distributed to the people involved in the measurement procedure for them to only concentrate on taking time measures of the tasks they are responsible for. The time measurement exercise was conducted in the subsequent three days after the activity identification. The result is presented in Table 24 in the column “Est. Unit Time (in min)”. The sample size of each day was around 250 products, which were inspected.

Table 24: Result table for determining the Time-Driven Activity-Based Costs.

Activity	% of all products	Quantity	Est. Unit Time (in min)	Total time	Cost driver rate (cdr)	Total assigned cost
A1	100%	15,180,538	0.05	815,530	0.02 €	250,564.84 €
A2	8%	1,265,045	0.09	114,299	0.03 €	35,117.48 €
A3	42%	6,325,224	0.15	938,246	0.05 €	288,268.40 €
A4	5%	759,027	0.20	153,602	0.06 €	47,193.03 €
A5	8%	1,180,709	0.26	308,252	0.08 €	94,708.04 €
A6	14%	2,108,408	0.24	504,401	0.07 €	154,973.27 €
A7	2%	253,009	0.26	66,054	0.08 €	20,294.58 €
A8	5%	759,027	0.12	89,987	0.04 €	27,647.73 €
A9	8%	1,265,045	0.14	175,092	0.04 €	53,795.47 €
A10	3%	506,018	0.22	110,434	0.07 €	33,929.87 €
A11	1%	84,336	0.10	8,486	0.03 €	2,607.16 €
A12	2%	253,009	0.18	45,542	0.06 €	13,992.29 €
A13	1%	210,841	0.20	42,801	0.06 €	13,150.16 €
A14	1%	126,504	0.21	26,102	0.06 €	8,019.66 €
A15	1%	84,336	0.06	5,098	0.02 €	1,566.22 €
A16	100%	15,180,538	0.05	734,305	0.01 €	225,609.31 €
A17	10%	1,475,886	0.13	187,287	0.04 €	57,542.46 €
A18	45%	6,789,074	0.16	1,059,291	0.05 €	325,458.48 €
A19	6%	843,363	0.23	190,983	0.07 €	58,678.05 €
A20	9%	1,307,213	0.21	280,567	0.07 €	86,201.83 €
A21	7%	1,096,372	0.22	242,725	0.07 €	74,575.17 €
A22	1%	126,504	0.08	10,101	0.02 €	3,103.40 €
A23	7%	1,054,204	0.13	141,315	0.04 €	43,418.01 €
A24	6%	927,700	0.19	179,768	0.06 €	55,232.12 €
A25	3%	379,513	0.18	66,752	0.05 €	20,509.07 €
A26	1%	168,673	0.10	17,636	0.03 €	5,418.41 €
A27	4%	632,522	0.19	122,621	0.06 €	37,674.46 €
A28	1%	126,504	0.06	7,225	0.02 €	2,219.76 €
A29	1%	210,841	0.07	13,705	0.02 €	4,210.64 €
Total cost				**6,658,205**		**2,045,679.39 €**

Besides the number of performed activities per year Table 24 also illustrates the time duration of performing the activities. Together with ccr, the cost of performing an activity, per time unit, becomes apparent, which represents how much money each activity consumes. After reviewing this result with experts they immediately identified room for improvement in the form of unnecessary performed activities, which are a consequence of process failure. A3 of Table 24 for instance is dedicated to an activity improving the appearance of the product with minor cosmetic treatment, which is a consequence of a process failure. With the TDABC method these activities become quantifiable. They account for 14% of total cost assigned, which represent 288,268.40 €. Improving the process would result in eliminating the activity A3, which implies significant cost reductions.

Table 25 presents the result of the capacity utilization analysis according to TDABC and combines the information of Table 23 and Table 24.

Table 25: Result table of capacity utilization according to TDABC.

Department	activity	# of products	time (in min)	total time	cdr	activity cost
Department A	A1	15,180,538	0.05	815,530	0.02 €	250,565 €
	A2	1,265,045	0.09	114,299	0.03 €	35,117 €
	A3	6,325,224	0.15	938,246	0.05 €	288,268 €
	...	...	...	...	...	...
	A29	210,841	0.07	13,705	0.02 €	4,211 €
Sum				**6,658,205**		**2,045,679**
Practical available time / Actual Cost				**10,992,000**		**3,377,203 €**
Under / over capacity				**4,333,795**	**39%**	**1,331,523 €**

Massive over capacity of 39% becomes apparent. This means from the installed capacity of 10,992,000 minutes per year 4,333,795 minutes can be considered as unused. This information expressed in costs reveals that 1,331,523 € per year are spent without proper utilization.

4.2.2.3 Cost Saving Opportunities

This section analyses a cost saving opportunity to decrease the identified over-capacity in Table 25. Hereby, the impact on costs of the proposed reorganization of the inspection system, as described in 3.3.3, is analyzed. The proposed model foresees to employ 18 permanent operators and 6 flexible operators instead of 24 permanent operators. The flexible operators take action and fill the position at the inspection system when a group of permanent operators take scheduled breaks.

TDABC can be applied to the new workforce organization. Full (permanent) and part time (flexible) operators account for the calculation of the new $pcrs$ according to (31). Full time operator's $pcrs$ remains at 6.67 hours per day as previously calculated. The operating time of the part time operators is calculated by summing up the scheduled break times of the groups of permanent operators. These are 80 minutes per group per day. Taking into account all three groups results in 240 minutes of operating time of the flexible workforce at the inspection stations.

Considering the 400 minutes operating time for full time operators and 240 minutes operating time for flexible operators, results in $pcrs_i$ of 96,000 minutes per year of one full time and 57,600 minutes per year of one part time operator.

In Table 26 the results of the old and new methods of organizing workforce are presented. While the old system refers to the as-is situation with 24 inspection operators, as described before, the new system foresees to operate with 18 full time and 6 part time operators (depending on the shift sizes the total number of operators is a multiple of 24, 18 or 6 respectively). Considering all shifts the old system employs in total 114.5 full time operators and the new system 90 full time and 30 part time operators. As demonstrated in 3.3.3 the system is capable to manage the production volume if 18 operators are constantly present at the inspection station.

Table 26: Comparison effects on costs of workforce organizing methods.

Inspection	Operators	pcrs	Cost
Required capacity		6,658,205	2,045,679 €
As-is system	114.5	10,992,000	3,377,203 €
Proposed system	120	10,368,000	3,185,484 €
full time	*90*	*8,640,000*	*2,654,570 €*
part time	*30*	*1,728,000*	*530,914 €*

The new system promises two benefits: (1) take advantage of an installed capacity reduction of 6%, which is equivalent to a cost reduction of 191,719€ per year; (2) the part time operators can be deployed for other tasks for 1,152,000 minutes yearly. This capacity is available for other tasks in the plant where other labor hours can be saved. However, the costs of 353,943€ for this capacity must be redistributed to use this capacity as calculated in Table 27.

Table 27: Available capacity of flexible work force for other tasks.

Other tasks	Operators	pcrs	Cost
part time	30	1,152,000	353,943 €

On the other hand even with the cost saving opportunities there is tremendous over-capacity. There is still room for improvement to reduce the installed over-capacity. However, one must not forget the influence of variability of human tasks, which are the reason to install such a high amount of over-capacity. This is specifically true if the buffer system is limited and a constant production flow must be guaranteed.

4.2.3 Remarks

This section presented the method of TDABC. With TDABC all activities become quantifiable in terms of costs. Furthermore, activities considered as unnecessary or activities as consequences of process failure become apparent together with their cost consumption. Thus, the motivation for the affiliated company to improve processes can be highlighted with the expression of the activities in costs.

As demonstrated, a CoQ system can be a good basis to a TDABC system if the capacity costs of the department under analysis have been considered during the CoQ cost collection exercise.

Besides the results for the affiliated company TDABC is relevant for this thesis. Elements of the methodology are used for a novel approach of cost modeling in section 4.4.

4.3 Process-Based Cost-Model

In this section the inspection process is analyzed by means of a Process-Based Cost-Model (PBCM). The PBCM allows understanding the effect of different design specifications and process operations on costs. In this context the as-is and the to-be situation are both financially modeled and a sensitivity analysis performed. Cost savings of the different operational conditions of the to-be system are compared to the as-is system. Having the financial model of the to-be system modifications of design specification are done, according to different inspection strategies, in order to estimate total process costs of each inspection strategy.

The scope of this analysis refers to the inspection system of the affiliated company depicted in Figure 15. Currently the inspection station operates 100% with manual labor and design changes based on automation are considered. The aim is to compare the as-is system design idea with different operational conditions of a to-be system regarding process costs. The to-be system includes different process configurations and different levels of automation as the inspection process step. One goal to achieve by the to-be system is to generate a process cost reduction of more than 50% compared to the as-is system.

The results are trend-setting for the further development process of the automated inspection system. Hereby, it is aimed to identify where to set focus within the development process of the to-be inspection system to meet a targeted process cost reduction. Since development is uncertain and an expensive task, knowing exactly which design specifications a system should target to can reduce costs significantly. The following analysis provides with directions which operational performance characteristics of the system elements have to be achieved to meet desired cost reductions.

4.3.1 Methodology to Develop a Process-Based Cost-Model

The framework of PBCM was introduced by Field et al. [68] and illustrated in Figure 56.

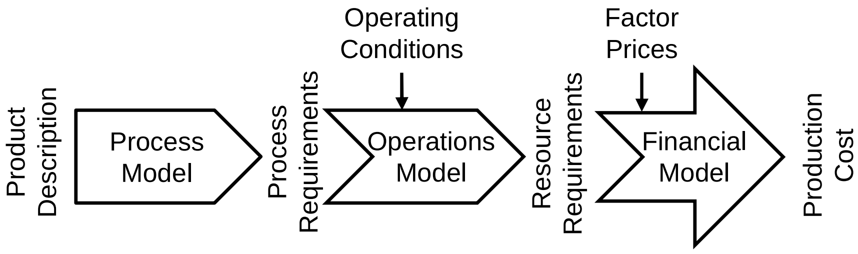


Figure 56: Process-based cost-modeling framework (Field et al. [68]).

The PBCM is a powerful tool to both engineering and management analysis. Subject to technical factors, such as cycle time, down time, efficiency rate, equipment and tooling constraints, costs can be modeled as a function. In that way the technical parameters become the driver for necessary quantities of factor resources.

The framework presented by Field et al. [68], as depicted in Figure 56, is composed by three sub-models. The process model describes all influencing factors to manufacture the product or part. These influencing factors take into account the processing parameters and requirements based on the products' geometrical characteristics and technical materials properties. Typical parameters are cycle times of process steps, machine capacity and tooling requirements, among others.

The operational model is fed with processing requirements together with operational conditions. Shift schedules, working hours and production volume are considered in the operational model. In consideration of these factors the total amount of equipment, labor, materials, floor space, energy, and other resources needed to accomplish a desired product output are determined.

The assignment of factor prices to the resource requirements, which are determined by the operational model results in the financial sub-model. Herein, costs are allocated over time and across products to achieve a production cost per unit output. Further refinement is possible to break down costs into its component parts, such as fixed and variable costs or other cost distribution logics.

The relationships constituted in the PBCM enable to perform sensitivity analysis in order to understand the effect on costs or on its component parts as operating and processing parameters change.

In the following details of the process flow and the identification of relevant costs are presented.

4.3.1.1 Process Flow Diagram

Figure 57 and Figure 58 present the process flow of the as-is and the to-be system. Both graphs are complemented with information of the inspection decision results on the respective process flow direction.

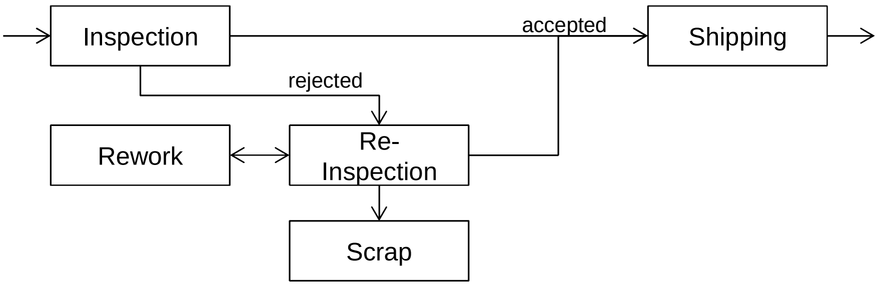


Figure 57: Process flow of the as-is system.

All products are appraised on conformance to requirements at the inspection system (Figure 57). Conforming items are accepted for customer delivery; nonconforming products are rejected and sent to be re-inspected. At the re-inspection station products with erroneous decisions of the first appraisal are released to be shipped to customers. Nonconforming recoverable products are sent to be reworked. After rectification reworked items are returned to be re-inspected and if matching requirements accepted for customer delivery. Hereby, iterative cycles can occur between rework and re-inspection for one specific product. Unrecoverable items are scrapped.

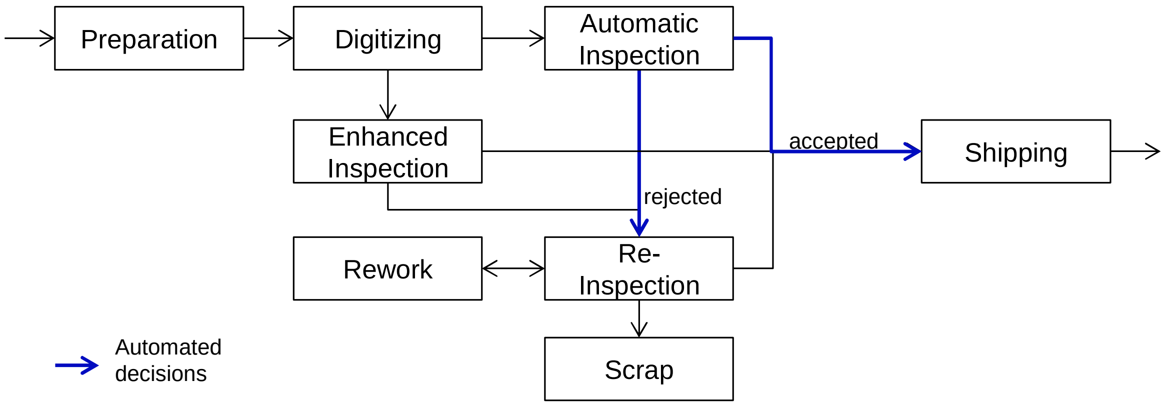


Figure 58: Process flow of the to-be system.

Figure 58 presents the to-be process flow, which adds preparation, digitizing and automation to the inspection process. It is necessary to include a process step to prepare the product for the technological advanced application. A defined range of products, which are disposed to be digitized, are forwarded to the automated inspection. Hereby, the criterion for a product to be among the defined range can be based on specific products, patterns, geometrics or other characteristics. The automated inspection forwards conforming products to be sent to the customer and nonconforming products to be re-inspected. The decision criteria are based on defined requirements. The ratio of automated decisions among all products is defined as the level of automated decisions.

Products that are not disposed to be digitized or the ones that were unsuccessfully digitized are sent to the enhanced inspection station for appraisal. This enhanced inspection step is an upgraded version of the inspection step in Figure 57. The decision options and the following process flow are identical to the inspection process flow in Figure 57 and its respective description. Cycle times relate to the preparation, digitization, the enhanced inspection, rework and re-inspection process step and can influence the costs of the system. The automated inspection is based on algorithms which run directly after the digitization within a server system and its cycle time is negligible.

To all process steps of Figure 57 and Figure 58 the relevant processing parameter must be identified and included to the operational model.

4.3.1.2 Identification of Relevant Costs

For the financial model relevant costs must be identified and formally described.

The total production volume is denominated with V_{gross}. V_{net} is the effective production volume reduced by scraped products from the scheduled production volume V_{gross}.

$$V_{gross} = \frac{V_{net}}{1 - scrap\ rate} \tag{32}$$

Nonconforming products may be recoverable or not based on the type of nonconformity and gravity of it. Thus the $scrap\ rate$ ($scrap\ rate\ \in [0-1]$) determines V_{gross} as consequence of process failures within the production steps. Since an inspection system is analyzed one must take into account that rejected items are re-inspected and reworked.

The financial model takes into account all previously defined cost components on a time (t) basis. In this case costs are considered on a yearly basis and divided in six categories. The categories are labor, machine, building, maintenance energy and capital:

$$C(t) = C(t)_{labor} + C(t)_{ws} + C(t)_{bldg} + C(t)_{main} + C(t)_{energy} + C(t)_{Cap} \tag{33}$$

If applicable material costs can be considered.

It is considered that all investments entail yearly costs and accrue for building and work stations. These investments are distributed across time and assumed to be paid in the form of an annuity. Having the annuity the cost can be allocated into a unit cost. For this purpose the capital recovery factor CRF is used to determine the annuities of the particular investments. The letter i denotes the type of investment (building or work station) and the letter j the process step for which the investment is done. The letter r represents the interest rate and L the length of time. With indication at hand the investment of space area or work station for process step j can be identified.

$$CRF_{ij} = \frac{r * (1+r)^L}{(1+r)^L - 1} \tag{34}$$

Work station cost can be calculated by the product of the capital recovery factor, the initial investment cost and the number of work stations (WS_j) considered for process step j. A work station is the aggregation of machines and equipment that is necessary to perform the process step. Therefore, workstation costs for process step j with capital investment $CI_{WS,j}$ are formulated as follows:

$$C_{ws,j} = CRF_{ws,j} * CI_{ws,j} * WS_j \tag{35}$$

Building cost with initial investment cost $CI_{bldg,j}$ for process step j can be expressed similarly:

$$C_{bldg,j} = CRF_{bldg,j} * CI_{bldg,j} \tag{36}$$

Labor costs are determined by the wages W_j for operators occupied in process step j and the number of operators required for a given production volume. In the case each workstation is occupied with one operator the total number of operators for one shift is equal to the number of workstations. And therefore workstations and numbers of operators are determined by cycle times and production volume. Given the prior information, only the number of shifts (NoS) is needed to calculate the total labor cost for all process steps.

$$C_{labor} = \sum_{j=1}^{n} W_j * WS_j * NoS \tag{37}$$

Energy costs are a product of energy consumption by the process step (E_j), operating time of the process (CT_j), production volume and energy cost for a time unit p_{energy}.

$$C_{enegy} = E_j * CT_j * V_{gross} * p_{energy} \tag{38}$$

Maintenance cost (C_{main}) are assumed to be a fraction (f) of the capital investment costs of the workstations and the yearly cost is incurred over lifetime as follows:

$$C_{main} = \frac{CI_{ws} * f}{L} \; with\; 0 \leq f \;\leq 1 \tag{39}$$

For all investments it is assumed that financial means stem from both own capital and loans. Following this train of thought, capital cost (C_{cap}) are the amount of interest to pay for the loan of total investment cost, discounted by own capital (OC). Note that i denotes the type of investment, j the process step and int the interest rate.

$$C_{cap} = \left(\left(\sum_{i}^{n} \sum_{j}^{m} CI_{i,j} \right) - OC \right) * int \tag{40}$$

The model takes into account cycle times of the respective machines and production volume and determines with the net amount of time per shift $pcrs_{shift}$ the operator demand. Machine costs are defined for an entire workstation for process step j in the respective department as done in (35). The number of workstations (WS_j) is defined as follows:

$$WS_j = \frac{V_{gross\ (shift)}}{\frac{1}{CT_j} * pcrs_{shift}} \tag{41}$$

It is necessary to relate what is known to the above presented formulation to create a sound financial model for further analysis.

4.3.2 Application Case a PBCM Approach

In the as-is situation the inspection station is humanly based and is aligned as a re-inspect rejects inspection system (for details on inspection strategies please refer to section 5). The to-be system situations take into account the integration of automation in the inspection process. The process configuration is portrayed in Figure 58. In the following a cost analysis is performed comparing the as-is to the to-be system. The analysis is twofold: Firstly, total cost and elements are compared. Secondly, a sensitivity analysis is performed by varying operating conditions of the to-be system in order to understand the effect of the different process parameters on cost.

4.3.2.1 Cost Structure Analysis of as-is Situation vs. to-be System

The as-is situation is similar to the design specifications as described in section 4.3.1.1. The development of a PBCM as described in 4.3 yields the numerical basis to generate graphs of the cost components as illustrated in Figure 59 and Figure 60.

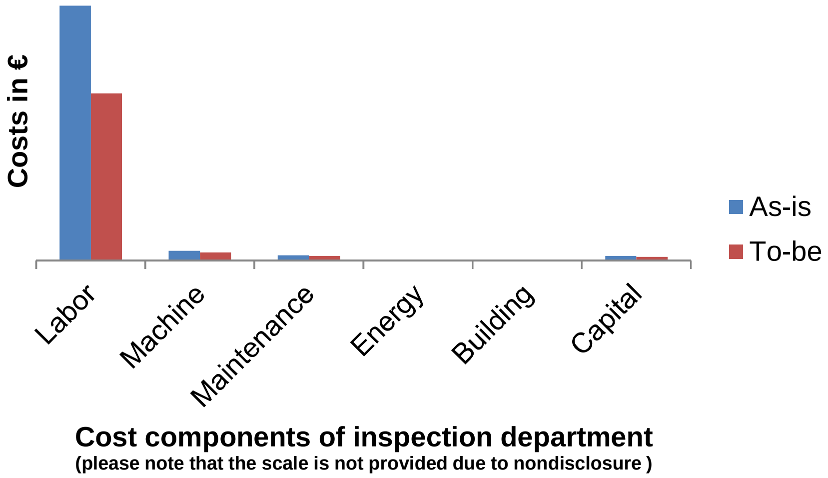


Figure 59: Breakdown of process costs of the as-is and to-be situations.

Figure 59 presents the cost breakdown structure of the inspection department. Costs are allocated in the sense of their disposition. Labor cost are by far the largest component of the cost structure for both the systems the as-is and the to-be system. As presented in Figure 59 cost reduction takes effect almost entirely through the decrease of labor. Given the identified greatest lever to reduce costs the next step is to understand in detail the elements where the cost reduction takes place.

Figure 60 illustrates the composing parts of labor costs for both the systems the as-is and the to-be system. The costs are presented in the sense of origin type and allocate the elements to the department's sub-divisions.

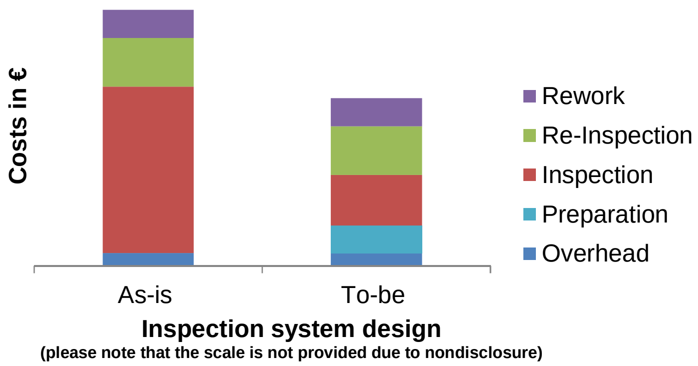


Figure 60: Component parts of labor costs of the as-is and to be situations.

Figure 60 reveals that the cost savings are achieved in the sub-division inspection. The other components, rework, re-inspection and overhead remain the same. The to-be system, as illustrated in Figure 58, requires an additional process step, preparation, which is presented as a cost item. However, the additional cost item preparation of the to-be system is absorbed by the huge cost reduction of the inspection.

There are two major drivers of the cost reduction. Firstly, the use of automated inspection reduces the number of products that need to be inspected with human labor at the enhanced inspection step (please refer to Figure 57 and Figure 58). Less human labor implicates less labor costs. Secondly, the to-be enhanced inspection task implicates a reduction of the cycle time, compared to the previous as-is inspection step, which is directly related to the number of required human workforce. The cycle time reduction is also endorsed by the new preparation process step, which was previously included in the inspection task. For this preparation task less qualified labor can be employed with lower wages.

The extent and the specific conditions of the cost reduction to take place are further analyzed in the next section.

4.3.2.2 Sensitivity Analysis of Cost Reduction for Varying Operating Conditions of the to-be System

The to-be system can be developed to operate at different operational conditions or performance characteristics respectively. In total there are four performance characteristics that determine the amount of cost savings. These are the cycle times for the process steps preparation, digitizing, enhanced inspection and the level of automated decisions (please refer to Figure 58). According to (41) cycle time determine the factor resources in the financial model and are thus directly related to cost.

In order to analyze the impact of all four performance characteristics two specific visual representations are presented. Each visual representation analyzes three components of the performance characteristics.

Figure 61 presents in the form of a map a sensitivity analysis that presents three highlighted regions. Each region represents one particular cycle time of the digitizing process step, which together with the other variables at the axis of abscissae and ordinate frame a highlighted region. Every combination of operational parameters of the to-be system within the highlighted region constitutes process cost savings larger than 50% compared to the as-is system. Hereby, the strategy of the analysis is performed by placing one performance characteristic with a steady value while the three remaining ones are altered. The parameters of the performance characteristics in Figure 61 relate to the elements of the process flow chart in Figure 58.

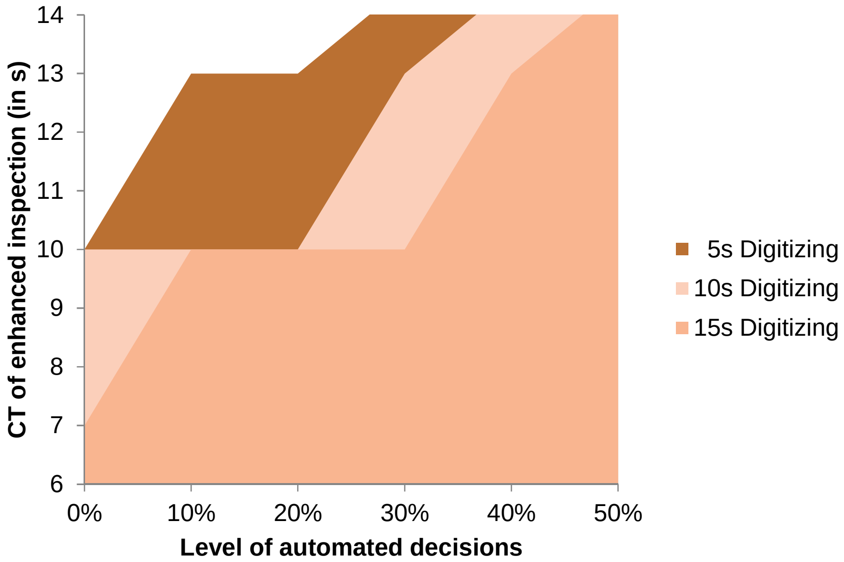


Figure 61: Combinations of performance characteristics for cost savings larger than 50% (1).

In Figure 61 there are four variables. While the cycle time of preparation is fixed to 10 seconds, there are other variables in of a certain range. These variables are the cycle time of digitizing the product, the level of automated decision making and the cycle time of enhanced inspection process (please refer to Figure 58). Digitizing the product is placed with three values of cycle time. The values of the scenarios are 5, 10 and 15 seconds for digitizing the product to take place. The x-axis variable describes the level of automated decisions and represents a percentage of the entire production volume for which an automated inspection can be achieved. The level of automated decisions refer to both conforming and nonconforming products and varies between 0 – 50%. The variable depicted in the y-axis refers to the cycle time of the enhanced inspection with a range of 6 – 14 seconds.

In order to achieve the targeted cost savings of 50% a 15 seconds cycle time of the digitization process requires a cycle time of the enhanced inspection of 7 seconds maximum. Increasing the level of automated decisions is rewarded with a less demanding cycle time for the enhanced inspection while at the same time targeted cost savings are still accomplished. This effect can be expressed in both directions. Thus, reducing the cycle time of the enhanced inspection process allows reaching a lower degree of automation for the decision making. In addition to the interdependencies of the two variables the cycle time reduction of product digitization amplifies the previously described effect. Reducing the digitization process expands the cost saving region and the requirements to the combination of performance characteristics of the remaining variables become less demanding.

Figure 62 presents as well a graph of combinations of performance characteristics that illustrates cost savings larger than 50%. In contrast with Figure 61 the cycle time of digitizing the product is fixed to 5 seconds and three scenarios of the preparation cycle time are presented. An analysis similar to the one done in Figure 61 can be performed but different insights are gained. As one can see the lowest regions of Figure 61 and Figure 62 are identical. Both represent identical cycle times of 15 seconds for preparation and 5 seconds for digitizing the product. As one can see, reducing the cycle time of preparation has a higher impact on expanding the regions of possible cost saving combinations than reducing the cycle time of digitizing the product.

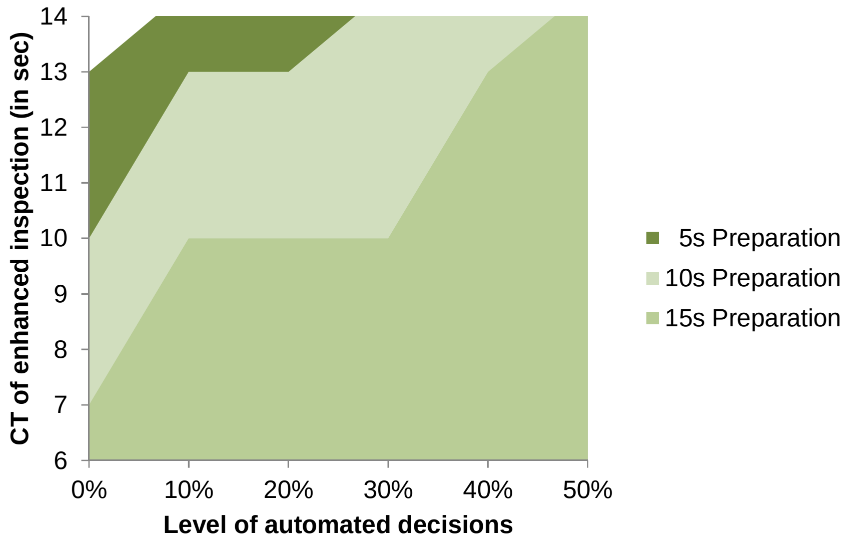


Figure 62: Combinations of performance characteristics for cost savings larger than 50% (2).

When observing Figure 61 and Figure 62 one can see distances of flat progression of the lines that confine the regions of cost savings greater than 50%. In Figure 62 for example the region of a cycle time of 15 seconds for preparation depicts a flat progression for the level of automation between 10 – 30%. This development indicates that an additional increase of automation is not rewarded with slower cycle times for the enhanced inspection task.

These types of insights are of great value to provide directions to the development of the system. For example, given a preparation cycle time of 15 seconds, digitizing the product at 5 seconds and guaranteeing a cycle time for the enhanced inspection of 10 seconds, the development stage of a 10% level of automated decisions is sufficient to reach the targeted cost reductions. This is specifically helpful due to unknown development cost differences of a system with an automation degree of 10% or 30%.

4.3.3 Remarks

The PBCM allows modeling both current manufacturing processes and planned future manufacturing processes. The financial model allows making cost comparison of different operational conditions. The sources of cost differences can be identified. Additionally, the indication for the development process of the future manufacturing process can be given to achieve targeted process costs.

4.4 Linking Process-Based Cost-Modeling and Time-Driven Activity Based Costing

This section presents an integrated approach of linking PBCM and TDABC. The integration provide with several benefits. Firstly, one can assess the costs of different operational conditions of to-be systems according to the PBCM results. With the integration of TDABC the determination of costs per time unit of individual system sub-units become apparent. Together with the activity times of the sub-units the sub-units' activity costs can be determined. Additionally, one can assess the capacity utilization of the desired to-be system.

4.4.1 Methodology

The methodology of the integrated approach is illustrated in Figure 63.

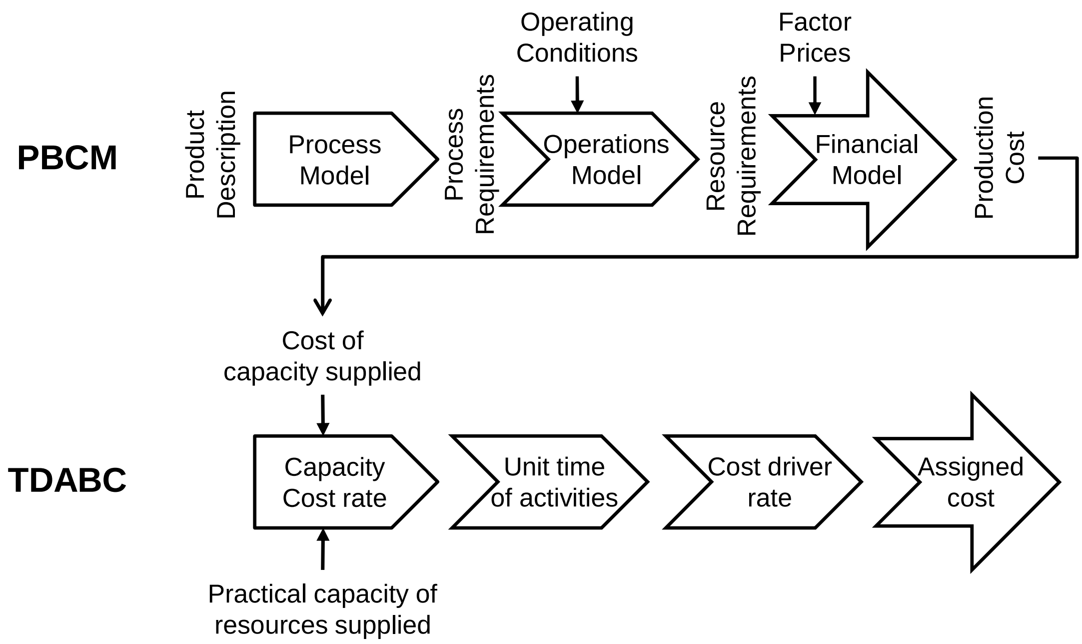


Figure 63: Methodology of a linked PBCM and TDABC system.

The aggregated process steps of developing a PBCM and a TDABC system design the linked PBCM and TDABC system. Hereby, the first part is identical to the PBCM methodology depicted in Figure 56. The second part is identical to the methodology depicted in Figure 55. One result of the PBCM is to identify sub-unit and total costs of a desired production system of certain operational conditions. These costs can be regarded as cost of capacity supplied and serve as an input for the TDABC analysis. After the determination of the practical capacity of resources supplied the analysis as described in 4.2 can be performed.

4.4.2 Application Case

This section presents an application case of the affiliated company of the previously presented linked methodology.

Hereby, different process configurations of the inspection system according to generic inspection strategies (Single inspection, re-inspect rejects and re-inspect accepts) are modelled with the PBCM approach. These costs serve as input to the TDABC approach where the costs of time units of individual sub-units within each of the inspection strategies are determined.

The generic inspection strategies (Single inspection, re-inspect rejects and re-inspect accepts) defined in literature are described in section 2.3. Both previously mentioned inspection systems – the as-is and the to-be – follow the approach of the re-inspect rejects strategy. This means that each rejected product after inspected is re-inspected. But each of the two inspection systems are composed with different elements within. These elements are technological advancement, the type of human tasks and process flow specifications. As shown, the PBCM analysis helped understanding the impact on costs of different operational conditions and furthermore provides with directions on where to set focus on within the development stage.

In order to complement the analysis the to-be process configuration of Figure 58 is adapted to match each of the two remaining inspection strategies, the single inspection and re-inspect accepts. For both newly generated process configurations an individual PBCM is generated as it was done for the re-inspect reject analysis. The three PBCMs provide with the total process costs for one specific combination of performance characteristics for each of the inspection strategies. The result of this process cost determination of the sub-units is depicted in Figure 64.

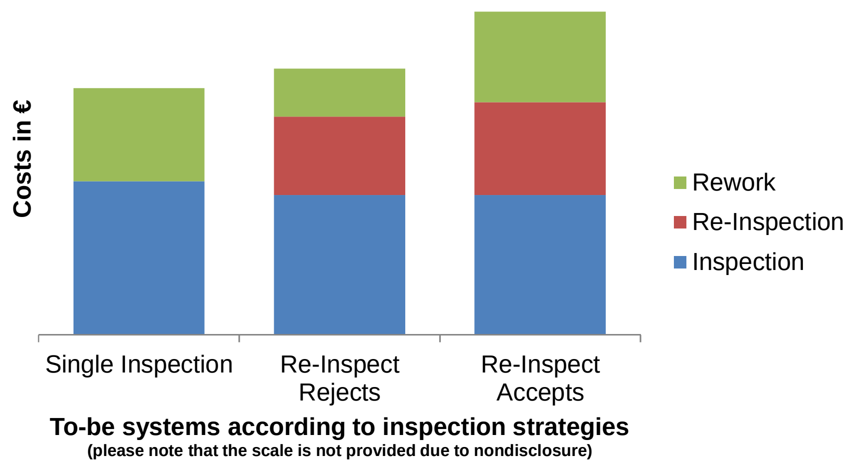


Figure 64: Process cost comparison of the three inspection strategies of the to-be system according to the PBCM approach.

The lowest process costs are achieved by following the single inspection strategy followed by the re-inspect rejects strategy. Re-inspecting accepted parts entails the largest costs. Comparing the cost components of Figure 64 one can see that the inspection costs are almost the same for each inspection strategy. By definition there is no expenses incurred for re-inspection for the single inspection strategy. Following the re-inspect rejects strategy is less costly regarding the re-inspection costs than the re-inspect accepts strategy. Reasons for that lie in the different numbers of re-inspected parts for each of the strategies. For example the re-inspect reject strategy inspects at least twice the net production volume in total. Once at the inspection station and a second time at the re-inspect accept station. The additional inspection effort for a re-inspect rejects strategy depends on the rejection rate of the preceding inspection station. Only rejected items are re-inspected and less effort might be necessary compared to the re-inspect accepts strategy. Expenditures for rework are the highest for the single inspection and the re-inspect rejects strategies. One can find reasons for that in the inefficiencies due to rejections of the first inspection stage. Incorrectly rejected conforming items create inefficiencies through unnecessary handling at the rework area. Furthermore conforming products might be incorrectly scrapped and epitomize unnecessary waste.

The identified sub-units costs in Figure 64 serve as an input for the TDABC system and epitomize the cost of capacity supplied. Together with the process times and quantities of the sub-units the time-driven activity costs of each sub-unit and according to each inspection strategy can be estimated. In the application case there are three sub-units: inspection, re-inspection and rework. Table 28 summarizes the activity costs after generating the PBCM and TDABC following the methodology in Figure 63.

Table 28: Cost per activity according to inspection strategies.

Activity	Inspection	Re-Inspection	Rework
Single Inspection	0.08 €		0.16 €
Re-Inspect Rejects	0.08 €	0.11 €	0.22 €
Retest Accepts	0.08 €	0.04 €	0.25 €

The activity costs for the sub-division inspection are equal for all the inspection strategies and account for 0.08 €. Single inspection does not incur activity costs for the re-inspection process. Although, process costs are higher for the sub-division re-inspection following the re-inspect accepts strategy than following the re-inspect rejects strategy, there is a different result for the activity costs according to Table 28. Re-inspect accepts activity costs are less than half than the activity costs for the re-inspect rejects strategy. The reverse picture of cost importance depends on the practical capacity supplied, the number of activities and the time to perform an activity (Please note that details are not revealed duet to NDA agreement).

The shown activity costs in Table 28 are used as input to perform the analysis in section 5.

4.4.3 Remarks

As demonstrated the link of PBCM and TDABC provides with estimations of total process and sub-unit costs of unknown systems. Additionally, activity costs of the (sub-) units can be determined based on time measures.

4.5 Summary

This chapter presented three cost modelling methods and suggested a novel approach. Hereby, the cost models can complement each other for further analysis.

A CoQ system helps identifying total quality costs as a post assessment of a given period. Part of these results can be used as input for an analysis according to the TDABC approach. The TDABC approach revealed cost saving opportunities after under-capacity utilization became apparent. PBCM is an effective method of analyzing and comparing costs of different process configurations and operational conditions. Combining and illustrating the data results of the cost modelling lead to a guiding map as indication for future development paths of to-be systems. The presented maps suit to quickly understand which combination of process parameters lead to the targeted process cost savings.

Linking PBCM and TDABC is rewarded with synergies of complementing insights. While PBCM assists in modeling to be-systems the TDABC helps identifying their corresponding activity costs.

The cost modeling approaches provide with additional information to analyze past performances, to assess to-be system costs and, to identify to-be activity costs but there remain some unanswered questions for a richer analysis. Although, there is a position to allocate external failure costs in a CoQ system the costs of those are difficult to capture or not measureable. None of the systems include the cost quantification of poor quality delivery.

The next chapter discusses an approach to assess the cost quantification of poor quality delivery as a consequence of an imperfect inspection system.

CHAPTER 5

5 Inspection Strategies

This section deals about the identification of a cost effective inspection strategy. After a cost advantageous strategy is found the circumstances are outlined of what leads to a strategy change if progress effects of improvement are assumed.

Hereby, the three generic inspection strategies, as introduced in 2.3, are assessed upon total quality costs. Each one of the three strategies are modeled in simulation and tested upon sensitivity by parameter variation. In contrast with the study in 3.3.2 this section analyzes the effectiveness of the inspection system on a macro level. While 3.3.2 analyzed the inspection system of the affiliated company very detailed, taking into account conveyor length and routes, this section considers the general layout options for inspection systems with 100% inspection. The emphasis is placed on the general arrangement of the inspection system according to specific inspection strategies.

Firstly, the proposed methodology is introduced. Accordingly to the methodology a case study from the affiliated company is presented. After the identification of a cost effective inspection strategy the question to answer is how to improve total quality cost more efficiently. Hereby, two improvement options are modeled: (1) process improvement through continuous improvement and (2) reliability enhancement of the inspection. It is assumed that the effect of the improvement options do not apply immediately but rather over time according to progress rates due to progress effects.

As a result cost effective regions of inspection strategies are outlined. Besides the identification of beneficial inspection strategies, evidence is collected that support the decision making to choose one improvement option over the other.

5.1 Background

As presented in 2.3 Ding et al. [90] propose three generic inspection strategies: Single inspection, re-inspect rejects and re-inspect accepts. These strategies are further investigated in this thesis to identify cost effective conditions to choose one strategy over the other. This is best quantifiable with Zakluta's [69] CoQ framework to capture cost of imperfect inspection systems. But a new element -progress effects- is taken into account that applies on improvement options.

In order to maintain the terminology of the literature the improvement options can be related to both approaches proposed by Mandroli et al. [91] – an inspection oriented strategy and a diagnosis oriented strategy. In this chapter the diagnosis oriented approach relates on the identification of individual NCs and assumes process improvement to take place upon progress functions. The inspection oriented approach involves the enhancement of the reliability of the inspection system based on individual NCs. The enhancement involves applying technology and its adjustment follows progress functions with corresponding progress ratios.

Progress functions are assumed to take effect because process improvement and process technology is the driver for improvement. Thus, having these drivers the underlying effect is termed as progress function [94]. In the following sections the term progress function is used to model the learning/progress effect. The variable b in equations (8) is referred to as the learning index and the variable p in equation (9) is referred to as the progress ratio.

The result presentation takes as example the illustration in Ding et al. [90], which presents regions of parameters where individual inspection methods are favorable. Although literature around testing and inspection strategies is insightful it does not take into account progress effects after implementing an improvement option. This research intends to fill this gap by analyzing the effect of learning according to a progress function on the inspection strategies in order to provide guidance on the following questions:

a) Given that a cost advantageous strategy is found, in what circumstances do progress effects lead to a switch in inspection strategies?
b) Which improvement strategy in which circumstances is cost beneficial to implement?

In order to answer these questions a methodology is established and a case study from the affiliated company presented.

5.2 Methodology

Figure 65 presents the developed methodology to create an inspection strategy map.

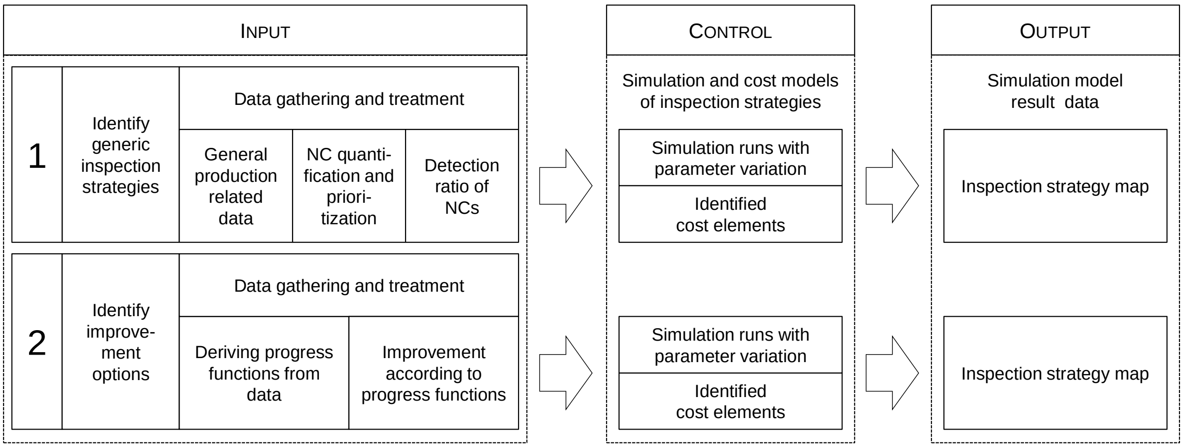


Figure 65: Methodology to develop an inspection strategy map.

The methodology, as illustrated in Figure 65, consists of three main steps. Inputs are transformed to outputs with adjustment control. The input is partitioned in two parts. Part one (1) comprises the identification of inspection strategies and part two (2) the identification of improvement options. To both parts the relevant data gathering and treatment must take place. With regard to inspection strategies relevant data relates to general production data, to NC quantification and prioritization and to estimates of detection ratios of the identified NCs. In order to focus on individual NCs the prioritization is done according to the developed TQM tool in 3.2.3. Relevant data related to improvement options cover progress functions derived from data and modeled accordingly. Progress ratios of progress functions of specific NCs are unknown and vary from companies and industries. This is why available data of the affiliated company is analyzed with the intention to find typical progress functions. If typical behavior is found it is used as reference for the model to test different levels of progress functions to understand their influences. The input data provides the simulation and cost models with data. Parameter variation allows performing sensitivity analysis to understand the model's behavior. The data output is consolidated at spread sheets to generate the inspection strategy map. Inputs are transformed to outputs with adjustment control. Simulation models of which each constitutes a specific inspection strategy are run with parameter variation to allow a sensitivity analysis.

Figure 66 illustrates the interrelation of the simulation and cost models in order to highlight the result generation process. Process and quality related data is the basis to develop the cost and simulation models. For each of the three generic inspection strategies an individual simulation model and cost model is generated. In order to analyze the different nonconformance levels for each general inspection strategy there is one set of ten sub-versions created. One set corresponds to one improvement option. In case there are two improvement options there are twenty sub-versions created. Having three inspection strategies makes it 60 subversions. Each sub-version corresponds to a specific general quality level between 1-10% of a nonconformance rate. Each of those sub-versions allowed varying the variables to test the different progress ratios (90%, 80% and 60%). The simulation output and cost parameters are consolidated at spread sheets. With further treatment the result in the form of an inspection strategy map can be generated. This map indicates regions of favorable inspection strategies in terms of costs. The process can be repeated with the identification of new NCs to focus on.

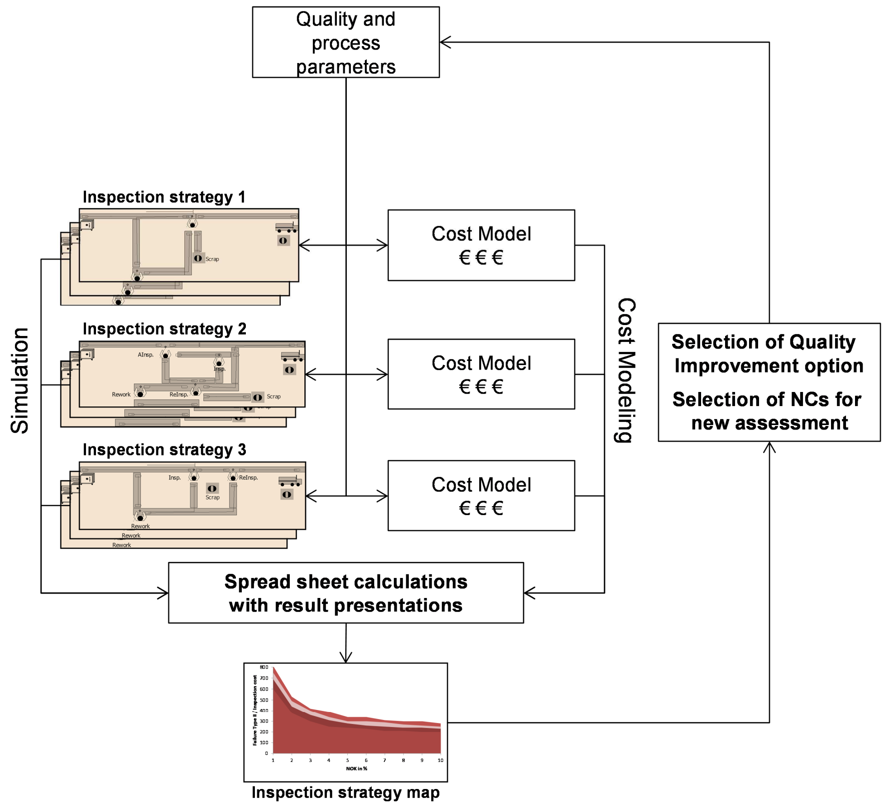


Figure 66: Interrelation of simulation and cost models.

Failure type II is the acceptance of nonconforming products at the inspection system. Its consequence is the delivery of a nonconforming product to the customer. In particular, it constitutes a delivered product with a specific nonconformity. The consequence is difficult to measure due to limited access to information in external data. While the number of warranty claims is measureable with internal data, the number of customer losses due to imperfect quality remains hidden in external data. However, the range of consequences reaches from warranty claims to customer losses or loss of potential new business due to questionable reputation. Failure type II cost can be regarded as penalty costs for delivering nonconforming products. Thus the ratio of failure type II cost to inspection cost provides an effective way to estimate the cost consequences of imperfect inspection systems.

5.3 Application Case

This section presents an application case of the methodology presented in 5.2. The application case relates to the affiliated company as introduced earlier in this thesis. The inspection strategies are the three generic inspection strategies as presented in 2.3.

Additionally, the detection ratios of NCs are estimated in order to determine the effectiveness of the inspection. With the data of the affiliated company it is aimed to generate inspection strategy maps to provide them with guidance on how to arrange their future inspection system.

In the following the data gathering exercise is explained and the simulation models presented. The results are discussed and a summary given.

5.3.1 Inspection Strategies: Data Gathering and Treatment

In this sub-section the data gathering and treatment for the first input part (1) of the methodology presented in Figure 65 is described. General production related data must be gathered, NCs must be quantified and prioritized for further improvement and their detectability determined.

5.3.1.1 General Production Related Data

General production related data, and the NC quantification of NCs relate to the quantification of production data in section 3.1. These corresponding data are used at the aggregated table in section 5.3.1.4.

5.3.1.2 NC Quantification and Prioritization

In order to identify and select the NCs that should be given priority to, the previously introduced prioritization tool is consulted (please refer to 3.2.3). In contrast with the previous case example given, within this section data from a different time period is the basis on which the tool is applied on.

There are numerous ways to set preferences at the tool presented in 3.2.3. For this application case four NCs were selected using the following criteria:

(1) Average weights of the attributes of the prioritization tool (Figure 81);
(2) an NC with a high occurrence which is severe(Figure 82);
(3) an NC with a high concentration to single machines at a previous production step which is also severe (Figure 83);
(4) an NC which is very difficult to detect and severe if it remains undetected

The results (Figure 81 to Figure 83) from the prioritization tool can be found in Appendix V. The NCs that appear in the critical area, based on the importance given to the attributes, are selected, and named NC W, NC X, NC Y and NC Z.

The fourth NC is not prioritized by the tool but is ranked highly among the attributes severity and detectability. Based on company feedback it is one important NC to select for further improvement.

5.3.1.3 Detectability and inspection error

The effectiveness of the inspection describes the detection of nonconforming products at the inspection station. At the inspection station there can be four appraisal results as illustrated in Figure 67. Two of the outcomes are correct and two are incorrect. In order to describe the detection probabilities, a ratio of a conforming product to be correctly identified as conforming can be attributed $(1-\alpha_i)$. The same applies for nonconforming products where the ratio of a nonconforming product to be correctly identified as nonconforming is identified $(1-\beta_i)$. This can be done on a refined manner to identify the detection ratios on an individual NC type i basis. Hence, the inspection error can also be determined. While α states the inspection error of conforming products, also known as rejecting conforming products, β states the inspection error of nonconforming products, also known as the acceptance of nonconforming products (Failure Type II).

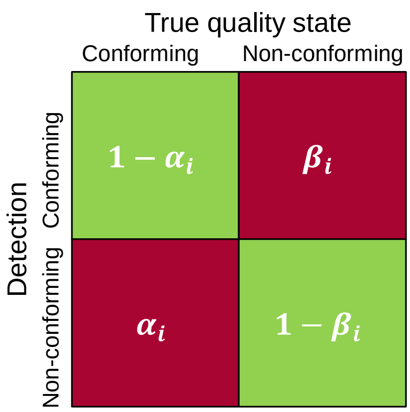


Figure 67: Possibilities of appraisal results at the inspection station.

After the estimation of detection ratios these can be used as detection probabilities. This term describes the probability of the correctness of the detection decision of a specific nonconforming or a conforming item at the inspection station.

The determination of the effectiveness of an inspection system is not a trivial task due to a number of reasons. Reasons range from imprecise appraisal tools to vague criteria definition for conforming items.

Internal and external data can be used to measure and quantify performance. With the internal data, if data is sufficiently insightful, complete and reliable, one can calculate the OK and NOK rate as well as the rework and scrap rate. Furthermore, one can analyze customer complaints and reflect on delivered product quality and might be able to conclude about which specific nonconformities the inspection station had missed. However, one must be aware that supposedly only the very severe nonconformities missed are reflected in those customer complaints and might only represent a fraction of the real value.

Another possibility to exactly measuring the effectiveness of the inspection is by performing an experiment. One could be re-inspecting all inspected products and validate the decisions. This method can be very effective but implies high efforts in the setting up the test. The re-inspection process may be evaluating a non-representative inspection system which operates on purpose thoroughly to not be exposed to the evaluator. Thus, to overcome the previously mentioned problematic one must either conduct a hidden test or be adequately satisfied with an approximate result. Thus measuring the effectiveness of the inspection is very time consuming.

Another possibility to estimate the effectiveness of the inspection is to interview experts upon their best belief of the effectiveness of the inspection. Conducting expert interviews is the method followed in this study. The interviewed experts are from the quality department and were asked to evaluate the effectiveness of the inspection. Participants of the interview process were the head of the quality department, the head of the production department and two quality engineers. One of the participating quality engineers is in charge of trainings and calibration measurements to the inspection system. The interview was conducted remotely with a questionnaire, an introduction provided, the purpose of the study to be performed and relevance of the information explained. Upon the provided introduction the experts filled out the questionnaire jointly in a group meeting.

The questionnaire, attached in Appendix IV, presents the estimated likelihood of specific NCs to be detected by the inspection station. The experts were asked to provide information about every single NC, the ones described in section 3.2.1, which exists and occurs at the end of the manufacturing process at the inspection station. The likelihoods of the current inspection system of detecting the NCs are used in the simulation system, which is presented in Table 29.

5.3.1.4 Selected NC Profiles

Table 29 presents the characteristics of the four selected NCs that are considered for the study. The fifth NC, NC R, is a symbolic NC that represents all remaining NCs to add up to a specific composed nonconformance rate.

Table 29: NC characteristics of selected NCs for further improvement.

NC	NC rate	Severity	Scrap rate	Rework rate	Detect-ability
NC W	0.52%	3.35	100%	0%	70%
NC X	10.12%	2	1%	70%	70%
NC Y	5.00%	3	32%	55%	70%
NC Z	0.64%	4	56%	43%	70%
NC R	83.72%	2	26%	48%	62%

Thus, the given example in Table 29 presents NC rates that add up to 100% and refers to a specific nonconformance level. Having this information allows calculating the fractions of nonconformance rates of the chosen nonconformities according to nonconformance levels (e.g. 1-10%). Alongside with the NC its supplementing data is presented from results of complementing data analysis. The NC rate, scrap rate and rework rate are results of the analysis presented in section 3.2.1. Severity and detectability stems from interviews as introduced in 3.2.3.4.3.

The effect of the composed NC rate is proposed by the author and formulated in equations (42) to (50). Equation (42) describes a set A consisting of all occurring NCs.

$$A = NC_{all} = \{NC | all\ occuring\ NCs\} \tag{42}$$

All occurring NCs are the sum of the number (x) of particular NCs.

$$NC_{all} = \sum_{i=1}^{n} NC_i * x_i \qquad with\ i, x \in N \tag{43}$$

Equation (43) can also be expressed with the selected NCs and an NC that is representative for all remaining ones (NC R).

Let M be the set of NCs that are selected for further investigation. Then all NCs are the sum of the selected and the remaining ones.

$$M = \{NC_j | NC_j \text{ is a selected one}\} \tag{44}$$

$$O = A \backslash M = \{NC_k | NC_k \text{ is not a selected one}\} \tag{45}$$

$$M \cap O = \{\emptyset\} \tag{46}$$

$$NC_{all} = \sum_{j}^{n} NC_j * x_j + \sum_{k}^{n} NC_k * x_k \tag{47}$$

$$with\ NC_j \in M \quad and \quad NC_k \in O \quad and \quad j, k, x \in N$$

Let NC R be the representative NC that incorporates all non-selected NCs. Then:

$$NC_R = \sum_{k}^{n} NC_k * x_k \tag{48}$$

And equation (47) can be stated as:

$$NC_{all} = \sum_{j}^{n} NC_j * x_j + NC_R \tag{49}$$

$$NC_R = NC_{all} - \sum_{j}^{n} NC_j * x_j \tag{50}$$

With this formulation the relative weights of the occurrences of the selected NCs remain the same for different nonconformance rates. Having the occurrence rates of the selected NCs isolated the decrease according to the progress rate can be applied.

After NC profiles are identified and relevant NCs selected the corresponding data for improvement options must be gathered and treated.

5.3.2 Improvement Options: Data Gathering and Treatment

In this section improvement options take place according to progress functions. After the improvement options are introduced real data is analyzed to derive progress ratios. Corresponding progress functions are applied on the data to be input for the next analysis – the simulation model.

The impact of two quality improvement options on quality costs for different inspection strategies are investigated. Quality improvement options consider different progress ratios over time, which should provide two answers to the following questions:

- Which improvement option is beneficial considering different progress rates for the improvement?
- If an optimal inspection strategy is found does progress over time suggest switching the initially defined strategy?

The two quality improvement options are *continuous improvement* of upstream process quality and *reliability enhancement of the inspection* at the quality inspection system at the end of the manufacturing line.

In this research *continuous improvement* assumes that production processes are incrementally improved over time and the nonconformance level decreases steadily according to a defined progress ratio. In the simulation model this is done by increasing the probability of producing conforming products for each simulation run.

The *reliability enhancement of the inspection* in this research represents the probability of the correctness of an appraisal decision. Referring to Figure 67 the two probabilities α and β are of interest to know, which represent the inspection error.

In the following sections the progress functions are presented. After, progress ratios are derived from real data general progress ratios are assumed and applied to the two different improvement strategies: *continuous improvement* and reliability enhancement *of the inspection*.

5.3.2.1 Deriving progress ratios from quality related data

At a first step real data from the quality department of the affiliated company is analyzed in order to identify suitable progress ratios for specific NCs. As mentioned earlier one of their main focuses is put on diminishing the scrap level. A certain reference scrap rate is set and

NCs beyond that value are selected for process improvement projects within interdepartmental teams. Those interdepartmental teams, in the following referred to as quality circles, meet on a weekly basis to analyze and discuss the progress, assess the situation and define points of action to improve the scrap rate. In the following, data is presented and analyzed of some NCs from those improvement projects. The period in the x-axis is given in months and the scrap level in percent at the y-axis. The purpose is to analyze the data to see if and to what extent improvement according to progress ratios took place. This may allow assuming average progress ratios, which can be applied to the selected NCs in 5.3.1.4.

The data on which the graphs Figure 68, Figure 69 and Figure 70 are based on was provided by the company's quality department.

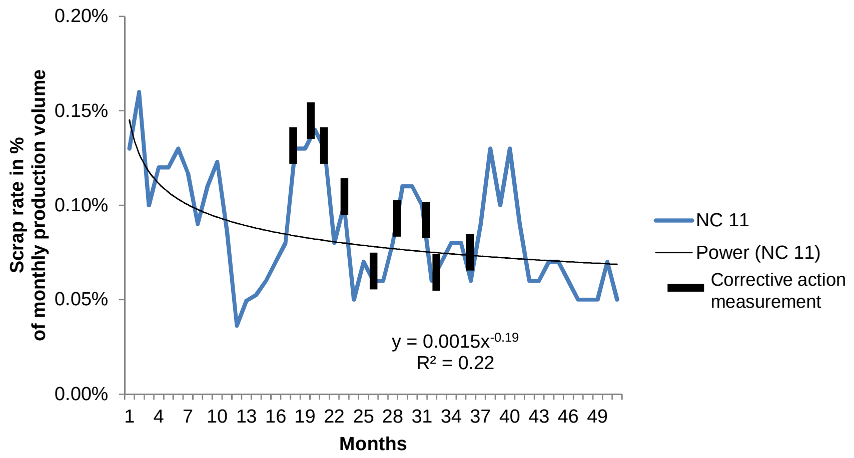


Figure 68: Scrap development of NC 11 over months with corrective actions.

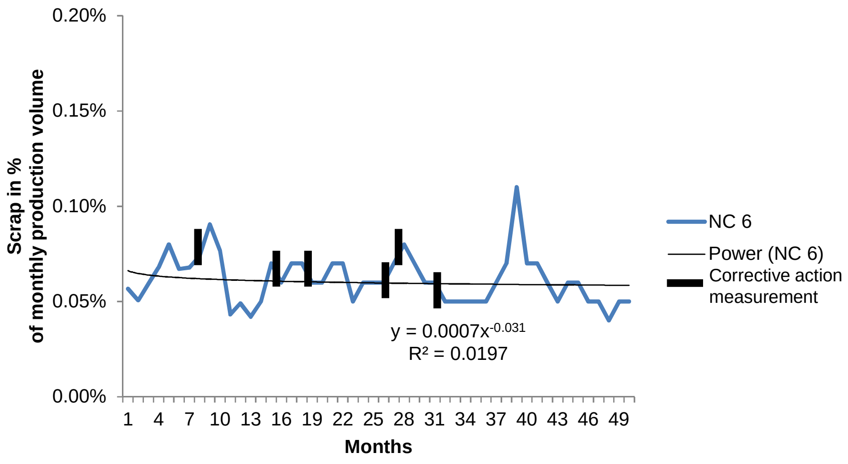
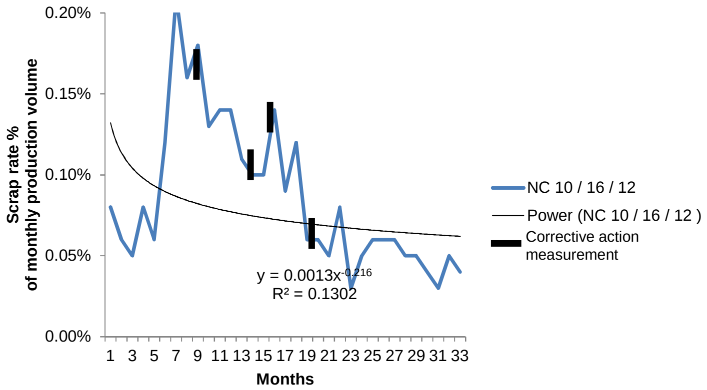
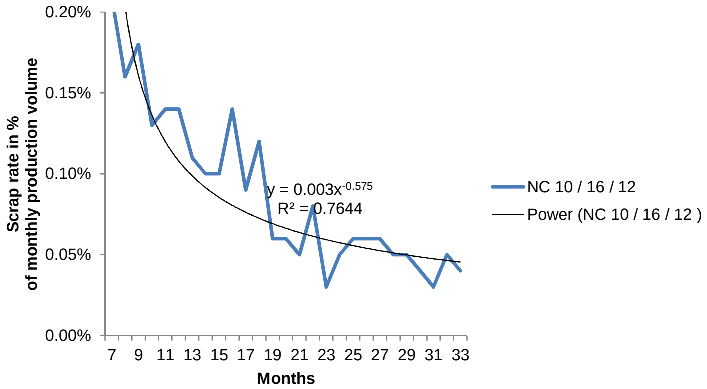


Figure 69: Scrap development of NC 6 over months with corrective actions.



a)



b)

Figure 70: a) Scrap development of NC 10/16/12 over months with corrective actions; b) Section of scrap development of NC 10/16/12

The graphs Figure 68, Figure 69 and Figure 70 show the development of scrap rates over a period of time of specific NCs. Figure 70 b) is a cut section of Figure 70 a), which is reduced by the first four months. The scrap rate is indicated as a percentage of the monthly production volume. The vertical indicators in the color black signal the introduction of corrective action measurement by the quality circles. Hereby, the measurements are related to process change, recalibration of machines, or to change of operator behavior. In some cases it could be a mixture of the aforesaid. Data is ambiguous and one can find both cases in which the scrap rate increases and decreases after the introduction of corrective actions. However, the development of the scrap rate is decreasing over time in all cases.

A trend line including its formula is added to each presented graph according to the power function. This formula suggests an approximation of the real data to the power function of the progress functions. The power values (learning indices) from equation (9) and their corresponding progress ratios are gathered in Table 30. According to the trend line NC 11 (Figure 68) has a progress ratio of 87.7%. The trend line of NC 6 (Figure 69) does not show much progress since the progress ratio is 97.5 %. Thus almost no progress takes place. NC 10/16/12 (Figure 70 a)) presents a progress ratio of 86.1. The abbreviated period of the scrap rate of NC 10/16/12 (Figure 70 b)) on the other hand, shows a very high progress ratio of 67.1%.

Table 30: Learning indices and corresponding progress ratios of analyzed scrap rates with $p = 2^{-b}$.

NC	Learning index b	Progress ratio p
NC 11	0.19	87.7%
NC 6	0.031	97.9%
NC 10/16/12 (a)	0.216	86.1%
NC 10/16/12 (b)	0.575	67.1%

According to equation (9) progress is related to the accumulative production volume. The graphs in Figure 68, Figure 69 and Figure 70 present the development of the scrap rate over months. Production volume of the company is steady over time. Daily and monthly production volume reaches almost the same value over time and small aberrations are negligible. Thus one can say that the accumulative production volume is proportional to time, which is given in months.

The presented graphs do show up to a certain point improvement according to progress ratios. Despite the decrease of the scrap rate, the decline is not stable and highly volatile. Understanding the clear relation of investment and improvement is preferable. However, the dataset does not provide evidence of investments to the corrective actions which led to improvement and will not be considered in this study.

The given examples presented cases of strong progress (67.1), moderate progress (86.1) and weak progress (97.9). The outcome of this analysis, the progress functions, of real data is the basis of the analysis in the next sections. Different progress functions are assumed to test the system for different levels of progress ratios in order to understand their influences.

5.3.2.2 Continuous Improvement According to Progress Ratios

The previous section presented analysis to derive progress functions from quality related data. Trend lines of volatile scrap rate show a relation to the power function. Some NCs show significant progress ratios, while very little progress took place for other NCs. As progress ratios vary across industries and within firms also each NC has its own behavior. In this study standard progress ratios are used to better understand the effect of learning. The applied progress ratios are 90%, 80% and 60%. 90% represents little progress, 80% moderate progress and 60% very strong progress to describe how much of costs remain after doubling the production volume.

For the inspection strategy *continuous improvement* it is assumed that individual prioritized NCs are selected as improvement projects. The effectiveness of the improvement is reflected in the form of nonconformance level reduction over time of the selected NCs. At the same time it is assumed that nonconformance levels of the other NCs remains unaffected. Thus a decrease of the overall nonconformance level is entirely attributable to the decrease of individual NCs occurrence.

Original progress ratios were derived from decreasing scrap rate, however, the assumed progress ratio in this study is applied on the nonconformance rate. The underlying reason is that a declining scrap rate is assumed to be a consequence of a declining nonconformance rate. This is based on the assumption that if a specific type of NC occurs historical data had proven what the recovery or scrap rate was. This is assumed to be true for all nonconformance levels that the ratio of recoverable products and scrapped products remain the same across different nonconformance levels.

Thus, in the following for every selected NC type (Table 29) the nonconformance rate experiences progress effects. The period for the effect to take place is assumed to for a period of 60 months (5 years). The applied standard progress ratios are 90%, 80% and 60%.

The effect of progress on the nonconformance level of individual NCs according to progress ratios are presented in Table 31 – Table 33. The period where progress takes place is 60 months and based on the specific nonconformance rates. The nonconformance rates vary between 1-10% as the effect of progress is tested for different nonconformance rates. The example in Table 31 relates to a nonconformance rate of 10%

Table 31: NCs with progress ratio of 90%/learning Index of 0.152 and initial nonconformance rate of 10%.

Name	NC W	NC X	NC Y	NC Z	NC R	NOK	OK
progress ratio p	90%	90%	90%	90%	100%		
learning index b	-0.152	-0.152	-0.152	-0.152	0		
Month 1	0.052%	1.012%	0.500%	0.064%	8.372%	10.000%	90.000%
Month 2	0.047%	0.911%	0.450%	0.058%	8.372%	9.837%	90.163%
Month ...	...	...	...	...	...	...	...
Month 60	0.028%	0.543%	0.268%	0.034%	8.372%	9.246%	90.754%

This particular example in Table 31 includes the general progress ratio 90% applied to the individual nonconformance rates of the selected NCs over a period of 60 months according to equation (8). The relative values of the nonconformance rate of the selected NCs earlier identified in Table 29 are applied to the overall nonconformance rate, which is presented in Table 31 assumed to be 10%. The sum of the nonconformance rates add up to the overall nonconformance rate. NC R is the resulting rate to add up to the overall nonconformance rate of 10%.

Applying equations (42) to (50) to the selected NCs in this application case is done in the following:

$$M = \{NC_{W}; NC_x;\ NC_y;\ NC_z\}$$

$$NC_{all} = NC_w * x_w + NC_x * x_x + NC_y * x_y + NC_z * x_z + NC_R$$

$$NC\ Rate = \frac{all\ NCs}{all\ produced\ parts} = \frac{NC_{all}}{n} = \frac{NC_w * x_w + NC_x * x_x + NC_y * x_y + NC_z * x_z + NC_R}{n}$$

$$NC\ Rate = 10\% = \frac{NC_w * x_w + NC_x * x_x + NC_y * x_y + NC_z * x_z + NC_R}{n}$$
$$= \frac{NC_w * x_w}{n} + \frac{NC_x * x_x}{n} + \frac{NC_y * x_y}{n} + \frac{NC_z * x_z}{n} + \frac{NC_R}{n}$$

$$\frac{NC_R}{n} = NC\ Rate - \left(\frac{NC_w * x_w}{n} + \frac{NC_x * x_x}{n} + \frac{NC_y * x_y}{n} + \frac{NC_z * x_z}{n}\right)$$
$$= NC\ Rate - (0.052 + 1.012 + 0.5 + 0.064)$$

$$\frac{NC_R^{10\%}}{n} = 8.372\%$$

Having this in mind, the next step is to apply equation (9) to the selected NCs NC W, NC X, NC Y and NC Z over a period of 60 months according to the corresponding progress ratio of 90%. In Table 31 one can see the starting nonconformance rate of the selected NCs and its decreased value after 60 months with the progress ratio of 90%. The nonconformance rate of the resulting NC R does not experience progress effects and remains the same. Hence the overall decline of the nonconformance level is entirely a result of the improved process quality in form of a reduced nonconformance level of the selected NCs. After 60 months the overall nonconformance level has improved from 10% to 9.246% by 7.5%.

Different progress ratios such as the general ones of 80% and 60% lead to a higher decrease of nonconformance levels as one can see in Table 32 and Table 33. 80% progress ratio promises an 11.9% improvement of the overall nonconformance rate from 10% to 8.808%. A 60% progress ratio results in a 15.5% improvement of the overall nonconformance rate from 10% to 8.452%.

Table 32: NCs with progress ratio of 80% and a nonconformance rate of 10%.

Name	NC W	NC X	NC Y	NC Z	NC R	NOK	OK
progress ratio p	80%	80%	80%	80%	100%		
learning index b	-0.3219	-0.3219	-0.3219	-0.3219	0		
Month 1	0.052%	1.012%	0.500%	0.064%	8.372%	10.000%	90.000%
Month 2	0.042%	0.810%	0.400%	0.051%	8.372%	9.674%	90.326%
Month ...	...	...	...	...	...	...	...
Month 60	0.014%	0.271%	0.134%	0.017%	8.372%	8.808%	91.192%

Table 33: NCs with progress ratio of 60% and a nonconformance rate of 10%.

Name		NC W	NC X	NC Y	NC Z	NC R	NOK	OK
progress ratio	**p**	60%	60%	60%	60%	100%	0%	
learning index	**b**	-0.737	-0.737	-0.737	-0.737	0	0	
Month	**1**	0.052%	1.012%	0.500%	0.064%	8.372%	10.000%	90.000%
Month	**2**	0.031%	0.607%	0.300%	0.038%	8.372%	9.349%	90.651%
Month	**...**	...	...	...	...	...	...	...
Month	**60**	0.003%	0.050%	0.024%	0.003%	8.372%	8.452%	91.548%

The same logic must be applied to different values of overall nonconformance rates (varying from 1-10%) for each of the three different general progress ratios (90%, 80%, 60%).

5.3.2.3 Reliability Enhancement of the Inspection According to Progress Ratios

While the previous improvement strategy focused on prevention, the one in this section deals about appraisal. Hereby, the detection ratios, as presented in Appendix IV, are assumed to improve according to progress ratios. The improvement is concentrated on the detection of the selected NCs listed in Table 29 with general progress ratios of 90%, 80% and 60%. According to Table 29 the detectability of each of the selected NCs (NC W, NC X, NC Y and NC Z) is evaluated to be 70%. The representative NC R is the arithmetic weighted mean of the remaining NCs. This is calculated as follows:

$$1 - \beta_R = \sum_{k}^{n} \frac{(1 - \beta_k)}{n} * x_k \tag{51}$$

Please note that the detectability $(1 - \beta)$ is in direct relation to the inspection error (β). Equation (51) considers all detection probabilities of the remaining NCs of the non-selected set O (please refer to equation (45)) multiplied by their occurrence number and divided by their total number.

As stated in 2.3, α and β represent the probabilities to commit inspection errors, referred to as type I and II. Rejecting conforming parts is expressed by α and accepting nonconforming parts by β. The progress ratio is applied on the parameter of the error rate β of the selected NCs in M (please refer to equation (44). Decreasing the error rate is taken as basis for the improvement according to progress rates. In Table 34 one can find the development of general progress ratios applied to the error rate (β) of NC W over a period of 60 months.

Table 34: Different progress rates on the non-detection rate of NC W.

Name		NC W	NC W	NC W
progress ratio	**p**	90%	80%	60%
learning index	**b**	-0.152	-0.3219	-0.737
Month	**1**	30.000%	30.000%	30.000%
Month	**2**	27.000%	24.000%	18.000%
Month	**...**	...	...	...
Month	**60**	16.100%	8.029%	1.468%

The lowest progress ratio of 90% decreases the error rate by almost 50% to 16.1%. The moderate 80% progress ratio decreases the error rate to 8.029%, while a 60 % progress ratio results in a 1.468% error rate as one can see in Figure 71. If a progress ratio of 60% for improving the error rate can be achieved the detection rate $(1-\beta)$ is at 98.532, which is close to perfect.

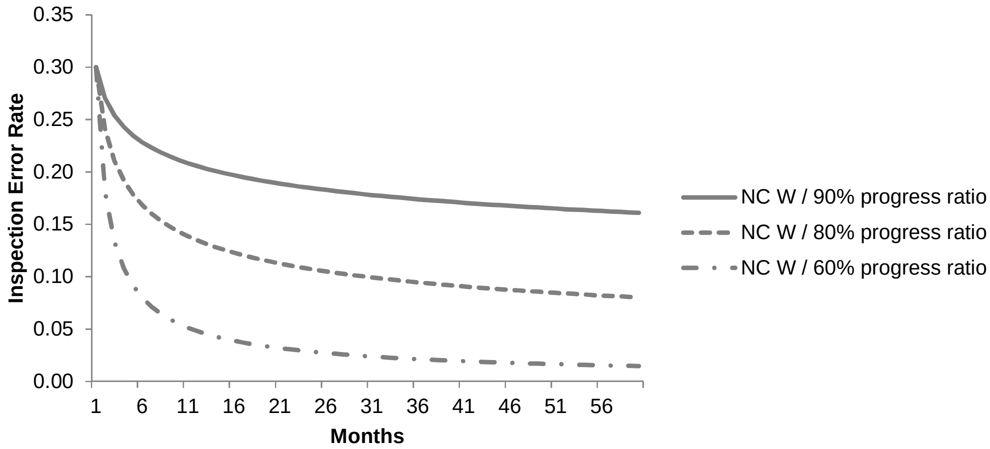


Figure 71: Decrease of the error rate according to general progress rates.

For the remaining selected NCs the progress effect is equal to the ones of NC W presented in Table 34 since all selected NCs share the same detection ratio according to Table 29.

In summary each remaining value after the general progress ratio is applied is selected and input into the simulation software.

5.3.3 Simulation of Inspection Strategies

In this section the developed simulation models are presented, which are used to test the three generic inspection strategy performances. Each one of the three generic strategies (single inspection, re-inspect rejects and re-inspect accepts) are modeled in discrete event simulation (DES) software (Arena; version 13.50.00000).

5.3.3.1 Simulation Models Description

Each individually modelled generic strategy is presented in Figure 72, Figure 74 and Figure 76. Complementing the models also the logic of the model's process flows is depicted in Figure 73, Figure 75 and Figure 77.

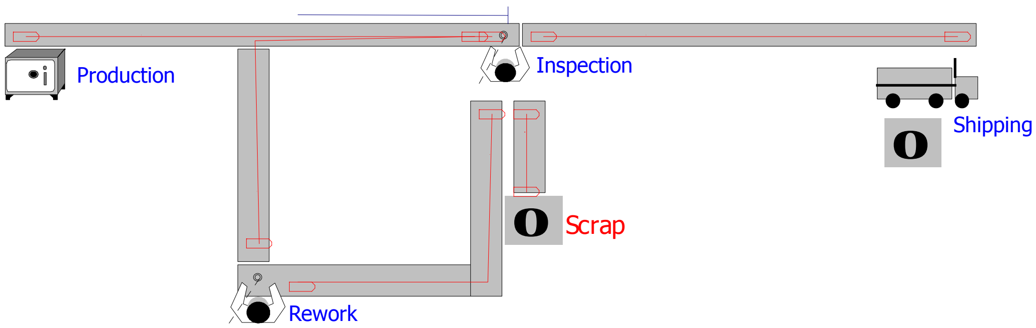


Figure 72: Simulation model of the single inspection strategy.

Figure 72 illustrates the process flow of the simulation of the single inspection strategy. All products are inspected after production. Conforming products are prepared for shipping and sent to the customer. Nonconforming products are rejected. Rejected products are, depending on the recoverability, sent to rework or are scrapped. A probability can be assigned to the decision to scrap or rework nonconforming product. The probability is generated through the previously measured rates. E.g. $S\%$ scrap and $1 - S\%$ rework. All reworked products are re-inspected. Prior to re-inspection the products are assigned with a new quality state, which can be conforming or nonconforming depending on the success rate of rework attempts. Thus, a reworked conforming item with a re-assigned quality state can be conforming or nonconforming. A reworked nonconforming item can be conforming or nonconforming after re-assignment of a new quality state.

In addition to Figure 72 the logic of the simulation model is depicted in Figure 73.

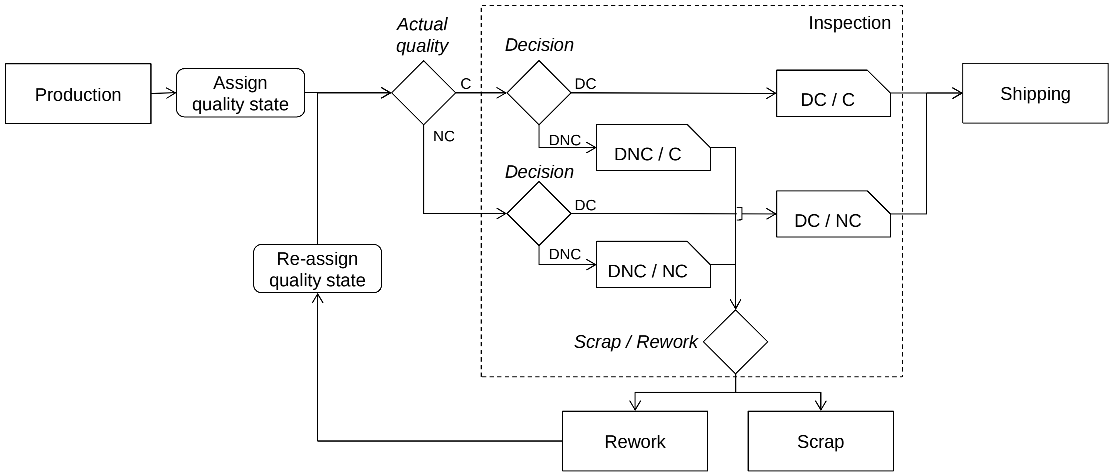


Figure 73: Logic of simulation model of the single inspection strategy.

At the production stage of Figure 73 the quality state is assigned as an attribute to each product. This can be done by defining a variable «QUALITY», which assigns a probability to the product's quality state. If the conformance level is δ%, then with a probability of $\frac{\delta}{100}$ the product gets a conforming and with $1 - \frac{\delta}{100}$ a nonconforming quality state assigned.

Before entering the inspection process the products are "artificially" separated upon their actual quality state. The separation serves the purpose of allocating different probabilities to the detection of conforming and nonconforming products. After separation a decision of the inspection is made on whether the product is conforming or nonconforming. All products with a decision to be conforming are sent to the customer. Decisions to be nonconforming are sent to either rework or scrap. In the model (Figure 73) all products are labeled upon their appraisal decision at the inspection. Since the products are separated prior to inspection, distinct categorization of their actual quality state and the decision correctness can be made.

This results in four outcomes, which are listed in Table 35:

Table 35: Possibilities of inspection decision results.

Abbreviation	Comment	Quality of decision
DC/C	Decision that product is conforming and product is actually conforming.	Correct decision
DC/NC	Decision that product is conforming but product is actually nonconforming.	Incorrect decision: Failure type II
DNC/C	Decision that product is nonconforming but product is actually conforming.	Incorrect decision: Failure type I
DNC/NC	Decision that product is nonconforming and product is actually nonconforming.	Correct decision

Complementing, Figure 74 and Figure 76 illustrate the simulation models of the strategies re-inspect rejects and re-inspect accepts.

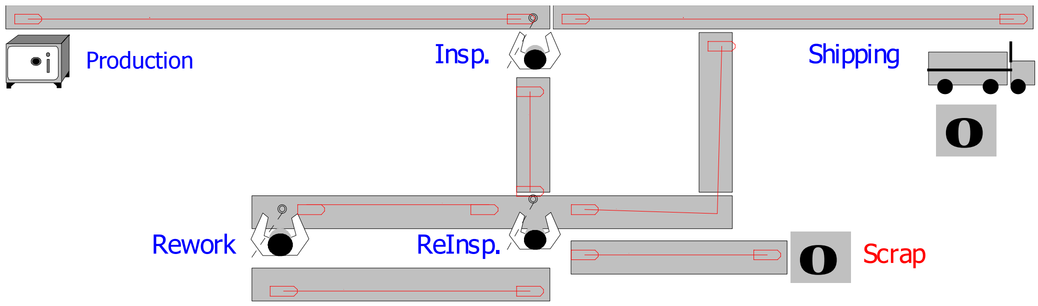


Figure 74: Simulation model of the inspection strategy: re-inspect rejects.

In contrast with the single inspection strategy the re-inspect rejects strategy in Figure 74 re-inspects all rejected and reworked items. Decisions can result in the product to be scrapped, reworked or to be sent to the customer.

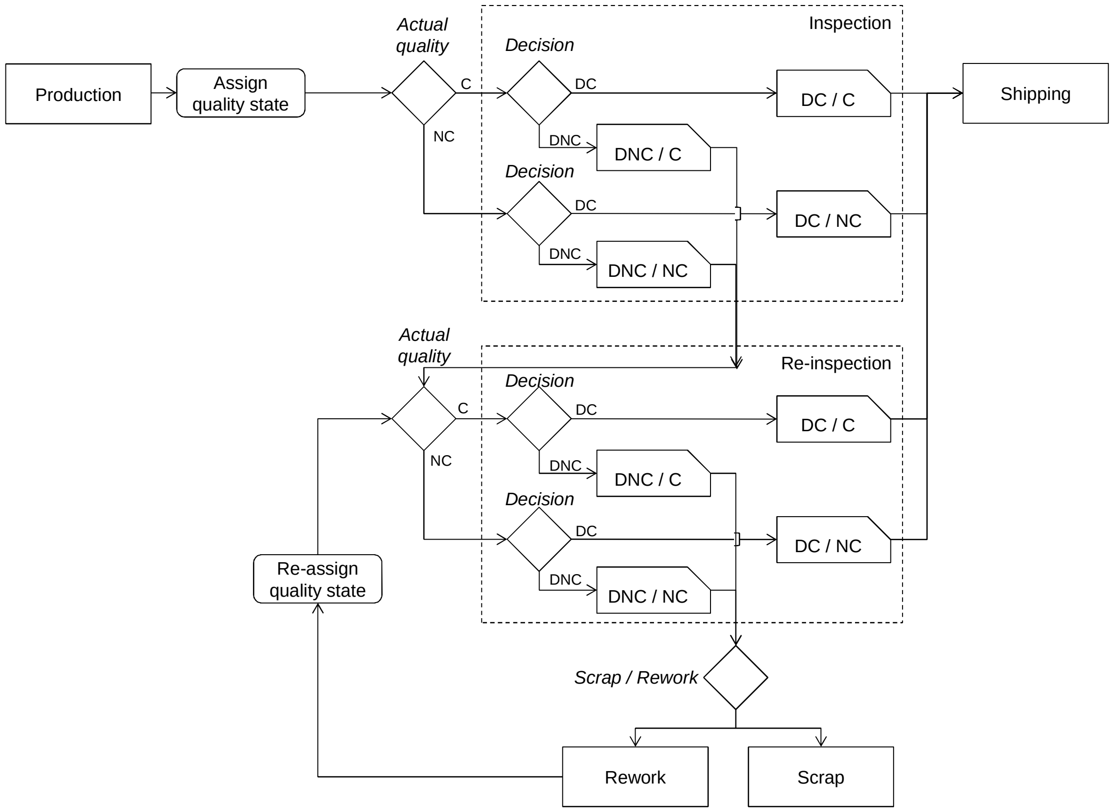


Figure 75: Logic of simulation model of the strategy: re-inspect rejects.

Figure 75 presents the logic of the simulation model of the strategy re-inspect rejects. The logic of the first inspection stage is identical to the single inspection model with the difference that all decisions of items to be nonconforming are sent to the second inspection stage. When products enter the second inspection stage, they are artificially separated according to their actual quality state, which can be conforming or nonconforming. After this separation a decision can be made which evaluates the product to be either conforming or nonconforming. Similar to the first inspection stage four outcomes can be achieved as presented in Table 35.

According to the re-inspect accepts strategy, presented in Figure 76, all conforming and reworked items are re-inspected.

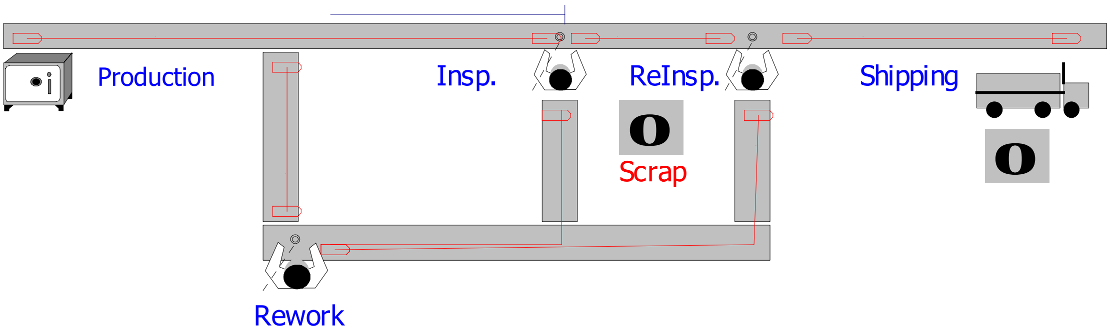


Figure 76: Simulation model of the inspection strategy: re-inspect accepts.

Figure 77 presents the logic of the simulation model of the strategy re-inspect accepts. The logic of the first inspection stage is identical to the single inspection model with the difference that all accepted conforming items are sent to the second inspection stage. When the products enter the second inspection stage they are artificially separated according to their actual quality state, which can be conforming or nonconforming. After this separation a decision can be made that evaluates the product upon conformance. Conforming products are accepted and sent to the customer, nonconforming products are rejected and sent to rework or scrap. Reworked items are re-inspected at the second inspection stage. Similar to the first inspection stage four outcomes can be achieved as presented in Table 35.

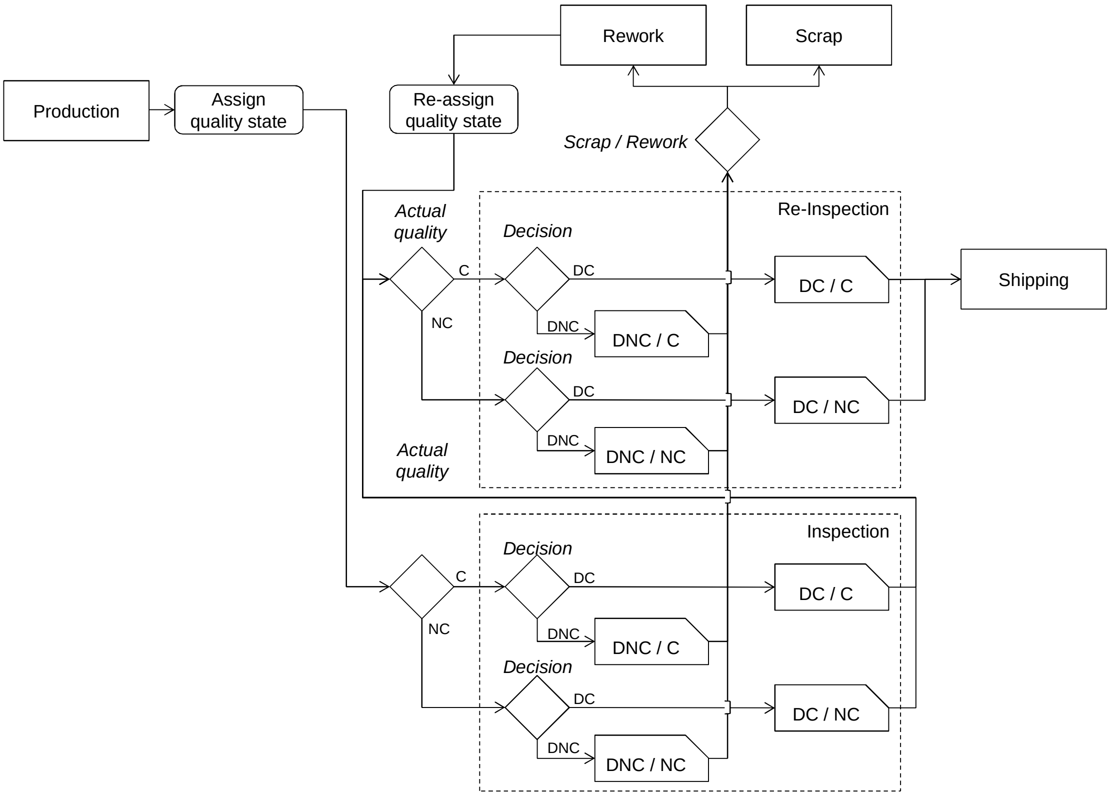


Figure 77: Logic of simulation model of the strategy: re-inspect accepts.

5.3.3.2 Input Variables for the Simulation Model

In order to generate the simulation results the simulation model is fed with values for the variables and attributes, which are listed in Table 36. While variables are globally valid within the simulation model, attributes are locally valid and attached to simulation entities as referred to in 3.3.1.

Table 36: Input variables into the simulation model.

Symbol	Name	Symbol	Name
λ	Production rate	S_i	Scrap rate of each of a nonconforming item i
δ	Probability of conforming item $\delta \in [0,\ldots,1]$	β_i	Probability of inspection error of a nonconforming item $\beta \in [0,\ldots,1]$ $i = 1,\ldots,n$
$NCRate_i$	Probability of nonconforming item i	Rec_i	Recoverability of a nonconforming item i at inspection
μ	Inspection process rate	ε	Re-inspection process rate
α	Probability of inspection error of a conforming item	γ	Rework process rate

In the simulation model items are produced with a production rate of λ. A produced item is with probability δ conforming or is nonconforming with probability $1-\delta$. Hereby, each nonconforming item corresponds to a type of NC (i) and is generated with probability $NCRate_i$. Items are inspected with inspection process rate μ. The variables α and β_i represent the probabilities to commit inspection errors. The inspection error of conforming items is denoted by α and the inspection error of specific nonconforming items by β_i. Rec_i is reserved for the recoverability of a nonconforming item at the rework station, which also can be individually attributed to the selected NCs. The variable S_i represents the scrap rate. They can be individually attributed to the selected NCs and are presented in Table 29. S_i and Rec_i are variables related to the inspection process and take effect for the products with an evaluation decision to be nonconforming (DNC in Figure 73, Figure 75 and Figure 77). The measured rate turns into a probability in the simulation model and the product is scrapped with probability S_i. The products that are reworked with rework process rate γ are recoverable with a probability of Rec_i. The recovered products are attributed to be a conforming product and enter the (re-) inspection process according to one of the simulation model's logic as in Figure 73, Figure 75 and Figure 77. The re-inspection process rate is denoted with ε. The remaining products that are not recovered remain in their nonconforming quality state and enter the (re-) inspection process again.

In the following study the overall nonconformance rate analyzed varies between 1-10% in steps of 1%, referring to the entire production volume. For each nonconformance rate the relative fractional value of the selected NCs as presented in Table 29 is calculated and input into the simulation model. This follows the assumption that the NC rate remains the same for different nonconformity levels. The input probabilities for the different nonconformance rates are depicted in Table 37.

Table 37: Probabilities of product to have a designated conformance rate.

Product conformance state	Probability of production with conformance state with general nonconformance rate									
	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
OK	0.99000	0.98000	0.97000	0.96000	0.95000	0.94000	0.93000	0.92000	0.91000	0.90000
NC W	0.00005	0.00010	0.00016	0.00021	0.00026	0.00031	0.00036	0.00042	0.00047	0.00052
NC X	0.00101	0.00202	0.00304	0.00405	0.00506	0.00607	0.00708	0.00810	0.00911	0.01012
NC Y	0.00050	0.00100	0.00150	0.00200	0.00250	0.00300	0.00350	0.00400	0.00450	0.00500
NC Z	0.00006	0.00013	0.00019	0.00026	0.00032	0.00038	0.00045	0.00051	0.00058	0.00064
NC R	0.00837	0.01674	0.02512	0.03349	0.04186	0.05023	0.05860	0.06698	0.07535	0.08372
Sum	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000

Exactly one nonconformance level is the basis for simulation run. For instance one simulation run can have a nonconformance rate of 8%. According to Table 37 in the simulation a new product is produced, which can have a probability of 0.92000 to be conforming and 0.08000 to be nonconforming. The 0.08000 is a composed probability of individual probabilities of specific NCs. The probability for the product to have an NC 33 is 0.00042, to have NC 2 is 0.00810, to have NC 6 is 0.00400, to have NC 27 is 0.00051 and to have NC R is 0.06698.

5.3.3.3 Data Output of the Simulation Model

After attributing values to the variables of the simulation model simulation runs can be started to obtain results. Results are numerous and one has to select the information of interest.

For each scenario the data regarding operational performance and quality results is recorded. The total number of delivered products, the number of operators seized is operational related data. The operators in the simulation are allocated to tasks at inspection, re-inspection (if applicable) and rework. Qualitative data obtained is the number of correctly and erroneously inspected products as a consequence of the assigned probabilities α and β_i. The result are the counted inspection results as presented in Table 35.

With that data one can calculate the total cost according to equation (1), the cost beyond perfect manufacturing.

$$CBPM(n_{co}) = C_{appraisal}(n_{co}) + C_{internal\,failure}(n_{co}) + C_{external\,failure}(n_{co}) \tag{1}$$

Hereby, the costs (c_s, c_{no}, c_{I_i} and c_R) as calculated in section 4.3.2.1 are inserted in equation (6) together with the simulation result data.

$$CBPM(n_{co}) = (n_s * c_s) + (n_{nco} * c_{nco}) + \sum_i \sum_j n_{I_{i,j}} * c_{I_i} + \sum_{k=1}^{l} n_{R_k} * c_R \tag{6}$$

All produced items in the simulation model are inspected and correspond to $\sum_i \sum_j n_{I_{i,j}}$. All scrapped items at the simulation model refer to n_s and all reworked items to $\sum_{k=1}^{l} n_{R_k}$. Failure type II corresponds to DC/NC in Table 35 and corresponds to n_{nco} of equation (6).

5.3.4 Results: The Inspection Strategy Map

The previous sections described the data gathering, the simulation model development and its input and output data. This section presents and discusses the obtained results.

The simulation models, as described in Figure 72 to Figure 76, are fed with input data to generate output data for the scenarios with general progress rates. The output data is gathered and crossed with the cost data identified with the linked PBCM and TDABC model in 4.4.2. The result presentation graphs are given in the format as presented in Ding et al. [90].

For each parameter combination the strategy that presents the minimum costs beyond perfect manufacturing ($cbpm$) is identified. The parameters on the x-axis are related to the nonconformance rate, which is varying from 1-10%. The parameters on the y-axis are related to costs. These are given as a cost ratio of the failure type II and inspection costs. With stable inspection costs the lever of the ratio is given by failure type II cost variation.

Figure 78 presents the result graph of the improvement option continuous improvement with areas of cost beneficial inspection strategies. The x-axis constitutes the nonconformance level varying between 1 and 10%. The y-axis represents the ratio of failure type II and inspection costs. The red shaded region presents the area in which the re-inspect rejects inspection strategy is less costly than the other two inspection strategies. The region in white is the area in which the re-inspect accepts strategy is cost beneficial compared to the other strategies. The boundary lines have a decreasing asymptotic trend. As the nonconformance level increases the lower gets the boundary line of the cost beneficial region of the re-inspect reject strategy. Hereby, the rapid decline at the lower nonconformance levels is noticeable. The results in Figure 78 of the boundary line with no progress allow producing four insights as follows: (1) The single inspection strategy is for these scenarios never beneficial. (2) If penalty costs are low (FTII/Insp < 200) for delivering products of imperfect quality the re-inspect reject strategy is always beneficial. (3) If penalty costs are high for imperfect delivered product quality than the re-inspect accept strategy is favorable. (4) The latter effect is more crucial for higher nonconformance rates than for lower ones. If one compares the cost ratio at 1% and at 10% then the cost ratio at 1% is three time as high than for a10% nonconformance rate. The boundary line expressed in penalty costs (FT II costs) can be three time as high for a nonconformance level of 1% compared to 10%.

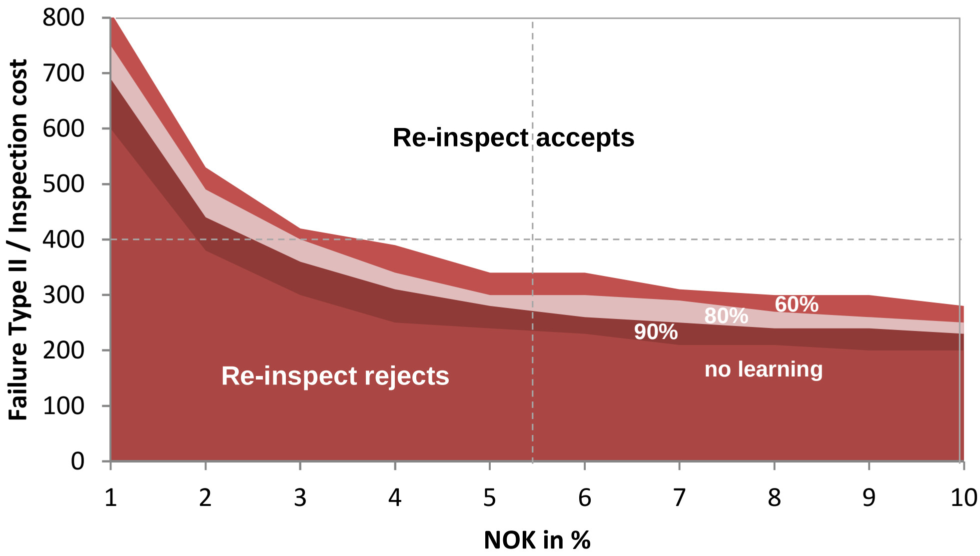


Figure 78: Result graph of improvement option continuous improvement with areas of beneficial inspection strategies with the impact of progress ratios stated in %.

Figure 78 also illustrates other boundaries presented in different shades of red. The different shades of red indicate the impact of progress. The boundary lines for no progress and the ones for the general progress ratios (90%, 80% and 60%) are illustrated. As a higher progress ratio takes place for the improvement option the boundary line expands the regions of a favorable re-inspect reject inspection strategy. This seems to take place constantly for all of the nonconformance levels. One can say that continuously improving processes concentrated to the prioritized NCs is rewarded with an extended region where the re-inspect reject strategy is beneficial. This is true for all nonconformance levels between 1-10%.

Figure 79 presents the result graph of the improvement option 'reliability enhancement of the inspection' with progress effects. The regions with a favorable re-inspect reject strategy are illustrated in different shades of blue. The boundary lines have a decreasing asymptotic trend. The base scenario with no progress is the same as for the one in Figure 78 and the same four insights apply.

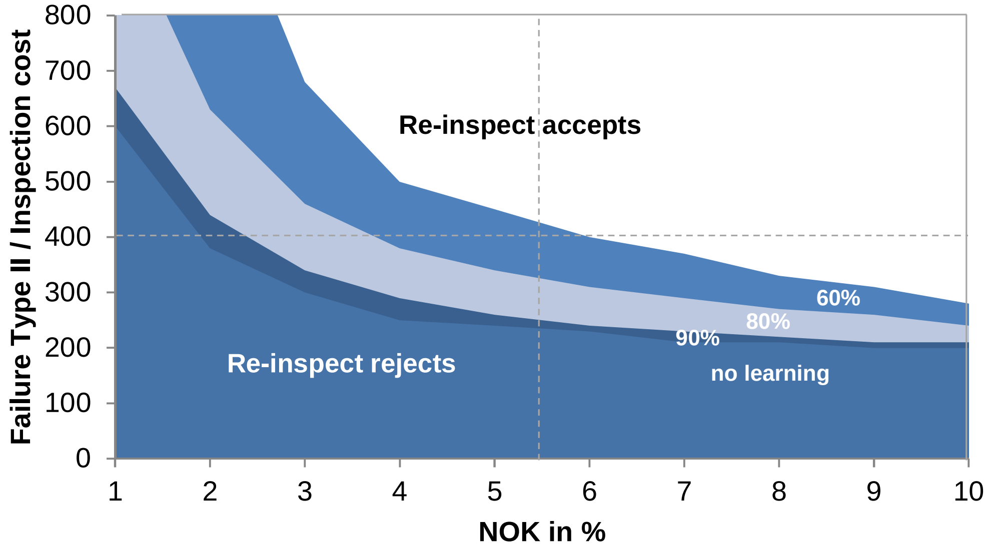


Figure 79: Result graph of improvement option reliability enhancement of the inspection with areas of beneficial inspection strategies with the impact of progress ratios stated in %.

In contrast with Figure 78, where the progress effect seems to take place equally for all nonconformance levels, Figure 79 presents a different picture. For lower nonconformance levels the values of the boundary line is significantly higher than for a higher nonconformance level. This effect seems to amplify as the progress effect gets stronger. In particular the effect of learning seems to be very strong for lower nonconformance levels.

Comparing both result graphs (Figure 78 and Figure 79) one can say that the progress effect for higher nonconformance levels (>7%) is not that much different. Although, enhancing the reliability of the inspection seems to have a marginally greater impact on the expansion of the re-inspect reject region. However, for lower nonconformance levels (<5) the option reliability enhancement of the inspection is preferable for better progress ratios than 90% ($p < 90\%$).

Although, distances of the shift of boundary lines due to progress effects seem to be marginal the difference in investments can be significant. Figure 80 shows the investment costs of the three inspection systems compared to each other with a reference to the re-inspect rejects investment costs (100%). As one can see the investment costs to implement a re-inspect reject inspection system are 10% higher than for the re-inspect rejects strategy. Thus, investments in progress have an effect to delay the boundary line of switching to another inspection strategy.

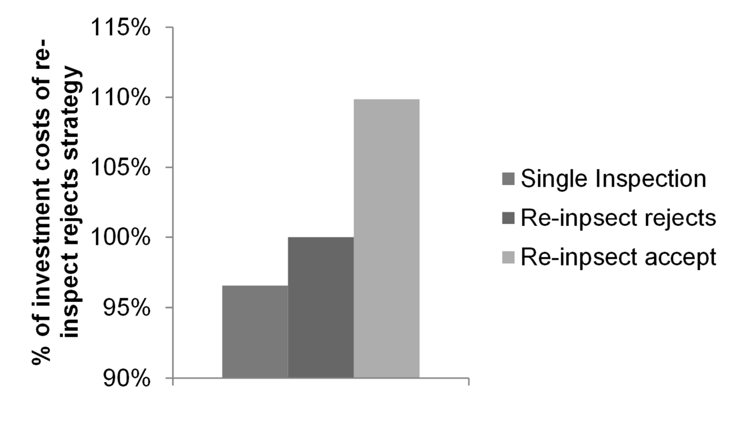


Figure 80: Investment costs of the three generic inspection strategies.

5.4 Summary

This chapter presented an integrated study to understand the effect of learning in the form of progress functions on improvement options for the identification of cost effective inspection strategies.

The study was integrated in terms of the integration of results and tools from previous chapters. Cost model results from section 4.4 and the application of the prioritization tool from section 3.2.3 were placed into the methodology. Besides the cost elements and prioritized NCs, general production and quality related data were included. Moreover, progress ratios of improvement options were considered. The control elements of the methodology were the simulation models, whose results in combination with cost elements and additional treatment presented the inspection strategy maps.

Results indicated that the identification of cost effective regions for inspection strategies can save investment costs if done prior to installation. The regions of parameter combinations where the cheaper re-inspect reject strategy is beneficial are identified. According to the results enhancing the reliability of the inspection with a focus on prioritized NCs is preferable to process improvement at lower nonconformance rates. This is true if high progress ratios can be considered.

This approach is useful to identify and determine a cost effective inspection strategy when the inspection is imperfect. Furthermore, it provides an estimation of quality costs of the effect of an imperfect inspection station.

CHAPTER 6

6 Conclusion

The purpose of this thesis was to study the impact of the prioritization of individual nonconformities (NCs) to be selected for quality improvement projects on the choice of a favorable, cost effective manufacturing inspection strategy. In order to target the derived research questions the problem was determined based on a real industrial company. Novel quality tools were developed, simulation models designed and cost modeling approaches considered to perform the study. In the following sections the thesis results and their implications are summarized and future research outlined.

6.1 Main Achievements and Contributions

This thesis has presented work to compliment and extend the scientific knowledge on the topic around total quality management. Both formal methodologies and practical modeling tools are provided to be applied by practitioners such as quality engineers from different manufacturing industries.

The first three research questions of the thesis concentrated on the development of tools in chapter 3. These served to quantify and better understand the as-is situation and to improve manufacturing processes. The first one addressed how to identify possible nonconformity root causes in mass production. Therefore, a methodology was developed and proofed with a case study from the affiliated company. Results indicate that with the applied visualization technique, in the form of a quality tool, it is possible to identify single machines that may be the originator of nonconformities. This approach demonstrated that the knowledge combination of different disciplines can result in new emerging methods, tools and knowledge.

The second research question targeted the prioritization of individual nonconformities based on relevant attributes. For this reason a theoretical prioritization model was formulated and illustrated with a case study from the affiliated company. The tool enables the user to prioritize among competing alternatives the most relevant ones based on customized, weighted multi-attributes.

The third research question focused on the elimination of unscheduled human variability at an inspection system. Therefore, a simulation model was developed, which represents in detail the affiliated company's inspection system. As a result not only bottleneck situations were identified but also indications for rectification of the identified problems given.

The second area of research questions (RQ #4 and RQ #5) focused on the identification of favorable inspection strategies in terms of total quality costs. Therefore, different cost modeling approaches were explored in chapter 4. On the one hand formal cost modeling approaches were applied to identify quality related costs and to assess the capacity utilization of cost centers. Furthermore, cost consequences of different performance characteristics of the to-be inspection system design were explored. On the other hand a novel cost modeling approach was introduced to estimate activity costs of to-be systems.

Results have shown that cost modeling constitutes an effective instrument to be applied within development processes of manufacturing systems. The estimation of cost consequences of different process parameters are adequate to be used during the development process. Moreover, the combination of cost modeling approaches can complement each other which allows exploring new dimensions of the analysis. The resulting cost elements were integrated in the methodology in chapter 5 to answer the last research question that aims to find a beneficial inspection strategy based on cost and quality parameters. Therefore, a formal methodology was designed consisting of quality related data from chapter 3 and cost elements from chapter 4. Moreover, it considered progress effects of improvement strategies from chapter 5 and simulation models, which relate to the inspection strategies. Results indicate that the consideration of progress effects on quality improvement options influences the regions of favorable inspection strategies. In summary improvement options should be chosen in consideration of minimizing total quality costs. Moreover, the choice of a right inspection strategy should be reconsidered after improvement projects are concluded.

This thesis presented significant scientific and practical contributions. Two quality tools were developed, which can be regarded as supplements to the scientific field of TQM. In user's perspective these tools are applicable for similar problems in other manufacturing industries. The prioritization tool can be applied to any portfolio decision making problem and can be integrated as a sub-step in scientific methodologies. Additionally, the application of detailed simulation models has proven to be a powerful instrument in solving particular problems of manufacturing systems. It is recommended to be used by practitioners. Moreover, a novel approach of cost modeling is devised. This approach integrates two established cost modeling techniques to present the user with new dimensions of cost analysis. Finally, there is a novel integrated approach proposed to determine the costs of imperfect inspection systems. Although there are studies that explored this area already none have taken into account progress effects of improvement options. The user can regard the strategy maps as recommendation for action if similar conditions hold. Furthermore, the results contribute to the discussion whether to invest in prevention or appraisal activities in order to reach the economic optimal point of quality costs.

All presented research in this thesis targets to improve quality in manufacturing. The consequences of improved quality in manufacturing are better and safer products for customers. This increases customer satisfaction and therefore has high impact on society.

6.2 Future Work

While initial findings are promising there are several limitations in this thesis, which may foster future research.

As a start, the success rate of the developed root causes analysis tool in chapter 3 applied in real industrial conditions must be identified to further validate this tool. The ability of identifying the root cause of NCs after having highlighted the possible contributor is of interest. The tool was developed to be used offline. With further development and integration to the installed IT system of a company it can turn into an online tool. Additional development can even automatically alert responsible persons when a critical value of concentration is exceeded and further investigations of root causes become attractive.

Further research regarding the prioritization tool chapter 3 could be directed towards validating the approach for different environments other than the one described in the application case of this approach. Additionally, improving the effectiveness of the approach from the perspective of the user can be investigated. For instance one must consider updating the input of attributes or redoing the evaluation of qualitative data over time. Also worth considering is the integration to the IT system of a company to comfortably treat and input quantitative data.

The analysis in chapter 5 takes into account progress effects on two separate improvement options: continuous improvement and the reliability enhancement of the inspection. However, a mixed approach that consists of both is neglected. In addition to that, the study is limited to the focus on individual nonconformities. It is assumed that learning is only concentrated on this one particular NC and spillover effects are neglected. This means that in the analysis done the improvement of the manufacturing process improves exactly according to the progress function of this one NC. Likewise is the mitigation of the inspection error only concentrated on a particular NC. However, there might be spillover effects directed to both directions. Changing the manufacturing process to eliminate one cause can influence other NC occurrences positively or negatively. And the improvement of the detection ratio can increase the general awareness at the inspection system, which might positively affect the other NC detection rates.

Moreover, the study in chapter 5 assumes the general learning model, the power function, suggested by Wright [92]. However, Yelle [93] state that there are other learning models discussed in literature. Considering other learning models may lead to different results. Furthermore, the study in chapter 5 presents a holistic view of learning at the inspection system, which can be regarded rather as organizational learning. Individual performances and learning rates are not considered and constitute a research opportunity [93].

The CoQ framework used in this research in chapter 5 does not take into consideration investments in prevention activities. The formulation of prevention effects on appraisal and failure, as done by Burgess [62], can be incorporated. Hereby, especially the relationship of investments (e.g. in prevention activities) on the progress rates [93] presents a research opportunity.

While this research has focused on inspection error and quality costs due to imperfect inspection also the positive quality improvement could be considered in future research.

Hereby, the estimation of the monetary worth of customer value as stressed by [13] could be included. When improving features of products this could be considered among the good delivered products in the model.

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Bibliography

[1] McNeil, I. (Ed.), “An encyclopedia of the history of technology,” Routledge, 2002.

[2] Petersen, N., Thomsen, M., Jürgensen, C. and Paulsen, P.D.C., „Leitfaden zur nordischen Alterthumskunde,“ Die Gesellschaft, 1837. [published in Engl. as: Thomsen, C., “A Guide to Northern Antiquities,” National Museum of Copenhagen, 1848.

[3] Womack, J.P, Jones, D.T and Roos, D., “The machine that changed the world: based on the Massachusetts Institute of Technology 5-million dollar 5-year study on the future of the automobile,” Cambridge, MA: Massachusetts Institute of Technology Rawson Associates (Free Press paperbacks), 1990.

[4] Shah, R., Chandrasekaran, A. and Linderman, K., “In pursuit of implementation patterns: the context of Lean and Six Sigma,” *International Journal of Production Research*, vol. 46, no. 23, pp. 6679–6699, 2008.

[5] Womack, J.P., and Jones D.T., “Lean thinking: Banish waste and create wealth in your organization,” New York, Rawson Associates, 1996.

[6] Hradesky, J.L., “Total quality management handbook,” New York: McGraw-Hill, 1995.

[7] Rampey, J. and Roberts, H.V., “Perspectives on total quality,” *Proceedings of Total Quality Forum IV*, Cincinnati, Ohio, November, 1992.

[8] Oakland, J.S., “Statistical Process Control,” 6th ed. Oxford: Butterworth-Heinemann, 2008.

[9] Gowen III, C.R., Stock, G.N. and McFadden, K.L., “Simultaneous implementation of Six Sigma and knowledge management in hospitals,” *International Journal of Production Research*, vol. 46, no. 23, pp. 6781–6795, 2008.

[10] Spath, Dieter, ed., “Ganzheitlich produzieren,“ Stuttgart: Logis, 2003.

[11] Gienke, H. and Kämpf, R., ”Handbuch Produktion: Innovatives Produktionsmanagement: Organisation, Konzepte, Controlling,“ Hanser Verlag, 2007.

[12] Fraunhofer-Institut für Arbeitswirtschaft und Organisation (IAO), “Ganzheitliche Produktionssysteme (GPS) – Einführung, Aufbau, Wirkungsweise, typische Bausteine,“ Stuttgart, 2002. Retrieved from http://www.produktionssysteme.iao.fhg.de/ (date visited: 14.11.2013).

[13] Juran, J.M., and Godfrey A.B., “Juran's quality handbook,” 5th ed. New York, NY: McGraw-Hill, 1999.

[14] Crosby, P.B., “Quality is free. The art of making quality certain,” New York: McGraw-Hill, 1979.

[15] Bounds, G.M., “Beyond total quality management. Toward the emerging paradigm,” New York: McGraw-Hill., 1994.

[16] Hellsten U. and Klefsjö B., “TQM as a management system consisting of values, techniques and tools,” *The TQM Magazine*, vol. 12, no.4, pp. 238–244, 2000.

[17] Ishikawa, K., “What is total quality control? The Japanese way,” Englewood Cliffs, N.J: Prentice-Hall, 1985.

[18] Feigenbaum, A.V. “TOTAL QUALITY CONTROL,” *Harvard Business Review*, vol. 34, no. 6, pp. 93–101, 1956.

[19] Feigenbaum, A.V., “Total quality control,” 3rd ed., New York: McGraw-Hill, 1991.

[20] Fotopoulos, C.B. and Psomas, E. L., “The impact of ‘soft’ and ‘hard’ TQM elements on quality management results, *International Journal of Quality & Reliability Management*, vol. 26, no. 2, pp. 150–163, 2009.

[21] Rahman, S. and Bullock, P., “Soft TQM, hard TQM, and organisational performance relationships: an empirical investigation,” *Omega*, vol. 33, no. 1, pp. 73–83, 2005.

[22] Ishikawa, K., “Guide to quality control,” Tokyo: Asian Productivity Organization, 1976.

[23] Mizuno, S., “Management for Quality Improvement: The 7 New QC Tools,” Cambridge, MA: Productivity Press, 1988.

[24] Shewhart, W.A., Economic control of quality of manufactured product, New York 501, 1931.

[25] Deming, W.E., “The new economics: for industry, government, education,” The MIT Press, 2000.

[26] Juran, J.M. and Gyrna, F.M. Jr., “Quality planning and analysis,” 2nd ed. New York: McGraw-Hill, 1980.

[27] Ishikawa, K., “Introduction to quality control,” Productivity Press, 1990.

[28] Ōno, T., “Toyota production system: Beyond large scale production,” Cambridge, MA: Productivitiy Pres, 1988.

[29] Shingō, S., “Zero quality control: Source inspection and the poka-yoke system,” Productivity Press, 1986.

[30] Taguchi, G., “Introduction to quality engineering: designing quality into products and processes,” 1986.

[31] Beckman, S, and Rosenfield, D., “Operations strategy: competing in the 21st century,” McGraw-Hill/Irwin, 2007.

[32] Dale, B.G. and McQuater, R., “Managing Business Improvement and Quality: Implementing Key Tools and Techniques”, Oxford : Blackwell Business, 1998.

[33] McQuater, R.E., Scurr, C.H., Dale, B.G. and Hillman, P.G., “Using quality tools and techniques successfully”, *The TQM Magazine*, vol. 7, no. 6, pp. 37-42, 1995.

[34] Thiagarajan, T. and Zairi, M., “A review of total quality management in practice: understanding the fundamentals through examples of best practice applications - Part I,” *The TQM Magazine*, vol. 9, no. 4, pp. 270–286, 1997.

[35] Ahmed, S. and Hassan, M., “Survey and case investigations on application of quality management tools and techniques in SMIs”, *International Journal of Quality & Reliability Management*, vol. 20, no. 6/7, pp. 795–826, 2003.

[36] Donauer, M., Azevedo, A. and Peças, P., "Evaluating the Effects of Soft TQM Tools on Quality Costs by Means of Simulation: A Case Study from the Automotive Industry”, *Proceedings of 20th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM)*, pp. 413 – 421, Helsinki, Finland, 2012.

[37] Fayyad, U., Piatetsky-Shapiro G. and Smyth P., “The KDD process for extracting useful knowledge from volumes of data,” *Communications of the ACM*, vol. 39, no.11, pp. 27-34, 1996.

[38] Choudhary, A.K., Harding, J.A. and Tiwari, M.K., “Data mining in manufacturing: a review based on the kind of knowledge,” *Journal of Intelligent Manufacturing*, vol. 20, no. 5, pp. 501–521, 2009.

[39] Harding, J.A., Shahbaz, M., Srinivas and Kusiak, A., “Data Mining in Manufacturing: A Review,” *Journal of Manufacturing Science and Engineering*, vol. 128, no. 4, pp. 969–976, 2006.

[40] Köksal, G., Batmaz, İ. and Testik, M.C., “A review of data mining applications for quality improvement in manufacturing industry,” *Expert Systems with Applications*, vol. 38, no. 10, pp. 13448–13467, 2011.

[41] Kumar, M., Antony, J. and Cho, B.R., "Project selection and its impact on the successful deployment of Six Sigma," *Business Process Management Journal*, vol. 15, no. 5, pp. 669–686, 2009.

[42] Hu, G., Wang, L., Fetch, S. and Bidanda, B., "A multi-objective model for project portfolio selection to implement lean and Six Sigma concepts," *International Journal of Production Research*, vol. 46, no. 23, pp. 6611–6625, 2008.

[43] Van de Water, H. and Vries, J.D., "Choosing a quality improvement project using the analytic hierarchy process," *International Journal of Quality & Reliability Management*, vol. 23, no. 4, pp. 409–425, 2006.

[44] Ahire, S.L. and Rana, D.S., "Selection of TQM pilot projects using an MCDM approach," *International Journal of Quality & Reliability Management*, vol. 12, no. 1, pp. 61-81, 1995.

[45] Singh, R.K., Kumar, S., Choudhury, A.K. and Tiwari, M.K., "Lean tool selection in a die casting unit: a fuzzy-based decision support heuristic," *International Journal of Production Research*, vol. 44, no. 7, pp. 1399–1429, 2006.

[46] Bilgen, B. and Şen, M., "Project selection through fuzzy analytic hierarchy process and a case study on Six Sigma implementation in an automotive industry," *Production Planning & Control*, vol. 23, no. 1, 2–25, 2011.

[47] Saaty, T.L., "The Analytic Hierarchy Process", New York: McGraw-Hill, 1980.

[48] Boran, S., Yazgan, H. R. and Goztepe, K., "A Fuzzy ANP-Based Approach for Prioritising Projects: A Six Sigma Case Study," *International Journal of Six Sigma and Competitive Advantage*, vol. 6, no. 3, pp. 133–155, 2011.

[49] Büyüközkan, G. and Öztürkcan, D., "An integrated analytic approach for Six Sigma project selection," *Expert Systems with Applications*, vol. 37, no. 8, pp. 5835–5847, 2010.

[50] Plunkett, J.J. and Dale, B.G., "A Review of the Literature On Quality-Related Costs," *International Journal of Quality & Reliability Management*, vol. 4, no. 1, pp. 40–52, 1987.

[51] Juran, J. M., "Quality Control Handbook," 1st edition. New York: McGraw Hill, 1951.

[52] Omurgonulsen, M., "A research on the measurement of quality costs in the Turkish food manufacturing industry," *Total Quality Management & Business Excellence*, vol. 20, no. 5, pp. 547–562, 2009.

[53] Campanella, J., "Principles of quality costs: Principles, implementation, and use," Milwaukee, Wisc: ASQC Quality Press, 1999.

[54] Williams, A.R.T., van der Wiele, A. and Dale, B.G., "Quality costing: a management review," *International Journal of Management Reviews*, vol. 1, no. 4, pp. 441–460, 1999.

[55] Freiesleben, J., "On the Limited Value of Cost of Quality Models", *Total Quality Management & Business Excellence*, vol. 15, no. 7, pp. 959–969, 2004.

[56] Schiffauerova, A. and Thomson, V., "A review of research on cost of quality models and best practices," *International Journal of Quality & Reliability Management*, vol. 23, no. 6, pp. 647–669, 2006.

[57] Sower, V.E., Quarles, R. and Broussard, E., "Cost of quality usage and its relationship to quality system maturity," *International Journal of Quality & Reliability Management*, vol. 24, no. 2, pp. 121–140, 2007.

[58] ASQC, "Quality Costs – What and How, American Society for Quality Control," New York, NY, p. 54, 1970.

[59] BS 6143, "Guide to the Economics of Quality: Part 2, 1990, Prevention, Appraisal and Failure Model," London: British Standards Institution, 1990.

[60] Juran, J.M.; Gryna, F.M., “Quality planning and analysis. From product development through use,” 3. edition. New York: McGraw-Hill, 1993.

[61] Deming, W. E., “Out of the crisis,” Cambridge, Massachusetts: Massachusetts Institute of Technology, Center for Advanced Engineering Study, 1986.

[62] Burgess, T.F., “Modelling quality-cost dynamics,” *International Journal of Quality & Reliability Management*, vol. 13, no. 3, pp. 8–26, 1996.

[63] Ross, D.T., "Structured analysis (SA): A language for communicating ideas," *Software Engineering, IEEE Transactions*, on 1, pp. 16-34, 1977.

[64] BS 6143, “Guide to the Economics of Quality: Part1, 1992, Process Cost Model,” London: British Standards Institution, 1992.

[65] Porter, L.J. and Rayner, P., “Quality costing for total quality management,” *International Journal of Production Economics*, vol. 27, p. 69, 1992.

[66] Busch, J.V. “Primary fabrication methods and costs in polymer processing for automotive applications,” Dissertation, Massachusetts Institute of Technology, 1983.

[67] Kirchain, R., Field, F., “Process-based cost modeling: understanding the economics of technical decisions,” *Encyclopedia of Materials Science and Engineering*, vol. 2,1718–1727, 2001.

[68] Field, F., Kirchain, R. and Roth, R., “Process costmodeling:strategic engineering and economic evaluation of materials technologies,” *JOM Journal of the Minerals, Metals and Materials Society*, vol. 59, no. 10, pp. 21–32, 2007.

[69] Zaklouta, H., “Cost of quality tradeoffs in manufacturing process and inspection strategy selection,” Master of Science, Massachusetts Institute of Technology, 2011. Retrieved from DSpace database (http://hdl.handle.net/1721.1/76133), April 2012.

[70] Cooper, R., and Kaplan, R.S., "Measure costs right: make the right decisions," *Harvard business review*, vol. 66, no. 5, pp. 96-103, 1988.

[71] Tsai, W.H., “Quality cost measurement under activity-based costing”, *International Journal of Quality & Reliability Management*, vol. 15, no. 7, p. 719, 1998.

[72] Kaplan, R.S. and Anderson, S.R., “Time-driven activity-based costing: a simpler and more powerful path to higher profits,” Harvard business press, 2007.

[73] Stout, D., and Propri, J., "Implementing Time-Driven Activity-Based Costing at Medium-Sized Electronics Company." *Management Accounting Quarterly*, vol. 12, no. 3, pp. 1-11, 2011.

[74] Clark, H. J. and Tannock, J.D.T., “The development and implementation of a simulation tool for the assessment of quality economics within a cell-based manufacturing company”, *International Journal of Production Research*, vol. 37, no. 5, pp. 979-995, 1999.

[75] Visawan, D. and Tannock, J., “Simulation of the economics of quality improvement in manufacturing: A case study from the Thai automotive industry”, *International Journal of Quality & Reliability Management*, vol. 21, no. 6, pp. 638–654, 2004.

[76] Jahangirian, M., Eldabi, T., Naseer, A., Stergioulas, L.K. and Young T., “Simulation in manufacturing and business: A review”, *European Journal of Operational Research*, vol. 203, no. 1, pp. 1–13, 2010.

[77] de Ruyter, A.S., Cardew-Hall, M.J. and Hodgson, P.D., “Estimating quality costs in an automotive stamping plant through the use of simulation”, *International Journal of Production Research*, vol. 40, no. 15, pp. 3835–3848, 2002.

[78] Spedding, T.A. and Chan, K.K., “System level improvement using discrete event simulation”, *International Journal of Quality & Reliability Management*, vol. 18, no. 1, pp. 84–103, 2001.

[79] Tannock, J. and Saelem, S., “Manufacturing disruption costs due to quality loss”, *International Journal of Quality & Reliability Management*, vol. 24, no. 3, pp. 263–278, 2007.

[80] Tannock, J.F.T, “Choice of inspection strategy using quality simulation”, *International Journal of Quality & Reliability Management*, vol. 12, no. 5, pp. 75–84, 1995.

[81] Gardner, L.L., Grant, M.E. and Rolston, L.J., “Using simulation to assess costs of quality”, *Proceedings of the 27th conference on Winter simulation*, Washington, DC, USA: IEEE Computer Society (WSC ’95), pp. 945-951, 1995.

[82] Son, Y.K. , Hsu Hsu, L.F., “A method of measuring quality costs”, *International Journal of Production Research*, vol. 29, no. 9, pp. 1785 – 1794, 1991.

[83] Omar, M.K., Sim, H.K., Murugan, S. and Muhamad, M.R., “The Impact of Costs of Quality: A Simulation Approach” *Proceedings of the International Conference on Industrial Engineering and Engineering Management*, pp. 1327 – 1331, Hong Kong: IEEE IEEM, 2009.

[84] Van Volsem, S., Dullaert, W. and Van Landeghem, H.. "An Evolutionary Algorithm and discrete event simulation for optimizing inspection strategies for multi-stage processes." *European Journal of Operational Research*, vol. 179, no. 3, 621-633, 2007.

[85] Vaghefi, A. and Sarhangian, V., "Contribution of simulation to the optimization of inspection plans for multi-stage manufacturing systems." *Computers & Industrial Engineering*, vol. 57, no. 4, pp. 1226-1234, 2009.

[86] Raouf, A., Jain, J.K. and Sathe, P.T., "A cost-minimization model for multicharacteristic component inspection," *AIIE Transactions*, vol. 15, no. 3, pp. 187-194, 1983.

[87] Duffuaa, S.O. and Raouf, A., "An optimal sequence in multicharacteristics inspection." *Journal of Optimization Theory and Applications*, vol. 67, no. 1, pp. 79-86, 1990.

[88] Duffuaa, S.O. and Al-Najjar, H.J., "An optimal complete inspection plan for critical multicharacteristic components," *Journal of the Operational Research Society*, vol. 46, no. 8, pp. 930-942, 1995.

[89] Korytkowski, P., Wisniewski, T. and Zaikin, O., "Multi-criteria approach to comparison of inspection allocation for multi-product manufacturing systems in make-to-order sector," *Control and Cybernetics*, vol. 39, no. 1 pp. 97-116, 2010.

[90] Ding, J., Greenberg, B.S. and Matsuo, H., “Repetitive Testing Strategies When the Testing Process Is Imperfect.” *Management Science*, vol. 44, no. 10, pp. 1367–1378, 1998.

[91] Mandroli, S.S., Shrivastava, A.K. and Ding, Y., “A survey of inspection strategy and sensor distribution studies in discrete-part manufacturing processes,” *IIE Transactions*, 38 (4), pp.

[92] Wright, T.P., “Factors Affecting the Cost of Airplanes,” *Journal of Aeronautical Sciences*, vol. 3, no. 4, pp. 490-502, 1936.

[93] Yelle, L.E., “The Learning Curve: Historical Review and Comprehensive Survey,” *Decision Sciences*, vol. 10, no. 2, pp. 302–328, 1979.

[94] Dutton, J.M. and Thomas, A., “Treating Progress Functions as a Managerial Opportunity,” *Academy of Management Review*, vol. 9, no. 2, pp. 235–247, 1984.

[95] Argote, L. and Epple, D. "Learning curves in manufacturing," *Science*, 247.4945, pp. 920-924, 1990.

[96] Badiru, A.B., "Computational survey of univariate and multivariate learning curve models," *Engineering Management, IEEE Transactions on*, vol. 39, no. 2, pp. 176-188, 1992.

[97] Alchian, A., "Reliability of progress curves in airframe production." *Econometrica: Journal of the Econometric Society*, pp. 679-693, 1963.

[98] Nadler, G., Smith, W.D., “Manufacturing Progress Functions for Types of Processes,” *International Journal of Production Research*, vol. 2, no. 2, pp. 115–135, 1963.

[99] Arrow, K.J., "The economic implications of learning by doing," *The review of economic studies*, vol. 29, no. 3, 155-173, 1962.

[100] Sheshinski, E., "Tests of the" learning by doing" hypothesis," *The review of Economics and Statistics*, vol. 49, no. 4, pp. 568-578, 1967.

[101] Baloff, N., "The Learning Curve--Some Controversial Issues," *The Journal of Industrial Economics*, vol. 14, no. 3, pp. 275-282, 1966.

[102] Levy, F.K., "Adaptation in the production process," *Management Science*, vol. 11, no. 6, B-136, 1965.

[103] Altiok, T., and Melamed, B., “Simulation Modeling and analysis with Arena,” Academic press, 2010.

[104] Rockwell Automation, “Arena-User's Guide,” Milwaukee: Rockwell Software, 2004.

[105] Rhoades, S.A., “The Herfindahl-Hirschman index (cover story)”, Federal Reserve Bulletin vol. 79, no.3, p. 188, 1993.

[106] Hirschman, A.O., “The paternity of an index”, *American Economic Review*, vol. 54, pp. 761–762, 1964.

[107] Hirschman, A.O., “National power and the structure of foreign trade,” University of California Press, 1969.

[108] Henderson, B., “The Experience Curve Reviewed: IV The Growth Share Matrix or the Product Portfolio,” BCG Perspectives, 135, 1973.

[109] Morrison, A. and Wensley, R., “Boxing up or Boxed in?: A Short History of the Boston Consulting Group Share/ Growth Matrix,” *Journal of Marketing Management*, vol. 7, no. 2, pp. 105–129, 1991.

[110] Abbott, A., “Methods of discovery: Heuristics for the social sciences,” 1st ed. New York: Norton, 2004.

[111] Lowy, A. and Hood P., “The Power of the 2 x 2 Matrix: Using 2 x 2 Thinking to Solve Business Problems and Make Better Decisions,” San Francisco: Jossey Bass, A Wiley Imprint, 2004.

[112] Carson, I.I. and John, S., "Introduction to modeling and simulation," *Proceedings of the 36th conference on Winter simulation*, Winter Simulation Conference, 2004.

[113] Kelton, W.D., Sadowski, R.P. and Sadowski, D.A., “Simulation with ARENA,” vol. 3. New York: McGraw-Hill, 2002.

[114] Carr, L.P. and Ponoemon, L.A., “The behavior of quality costs: classifying the confusion”, *Journal of Cost Management Practices*, No. Summer, pp. 26-34, 1994.

[115] Donauer, M., Peças, P. and Azevedo, A., "Nonconformity Root Causes Analysis Through a Pattern Identification Approach." Advances in Sustainable and Competitive Manufacturing Systems. Springer International Publishing, pp. 851-863, 2013.

[116] Donauer, M., Peças, P., Azevedo, A.L., “Nonconformity Tracking and Prioritization Matrix: An Approach for Selecting Nonconformities as a Contribution to the Field of TQM”, *Production Planning & Control*, forthcoming 2014.

[117] Silva, E., Donauer, M., Azevedo, A., Peças, P. and Henriques, E., “A case study evaluating the impact of human behavior on a manufacturing process in-line with automatic processes by means of a simulation model”, Proceedings of the IEEE International Conference, (Bangkok, Thailand), Industrial Engineering and Engineering Management (IEEM), 2013.

Appendix I – Operators Inspection Performances

Operator	Mean	STD	ni
1	38	17	2971
2	37	21	2656
3	27	14	4150
4	39	18	2916
5	37	19	3109
6	30	18	3388
7	39	17	3076
8	37	20	3116
9	34	18	685
10	33	14	679
11	32	18	715
12	27	15	723
13	37	20	667
14	23	14	809
15	35	19	3108
16	31	20	691
17	30	12	723
18	30	15	737
19	31	18	700
20	38	15	605
21	34	24	557
22	31	19	575
23	29	16	724
24	35	19	624

Appendix II – Overview of Prioritization Tool Input

Weights	33%			33%			33%			100%							0%			0%		
NC	Occurrences	Scaled	100 * X_1	Severity	Scaled	100 * X_2	Detection	Scaled	100 * X_3	HHI_1	Scaled	100 * Y_{11}	HHI_2	Scaled	100 * Y_{12}	max(Y_{11}, Y_{12})	Customer complaints	Scaled	100 * Y_2	Scrap rate	Scaled	100 * Y_3
NC1	7026	1.00	100	1.33	0.27	29	3	0.3	30	0.0	0.2	20	0.1	0.1	11	20	0.2	0.2	20	0.01	0.01	1
NC2	5999	0.85	85	2.00	0.40	43	3	0.3	30	0.1	0.4	40	0.2	0.3	27	40	0.2	0.2	20	0.00	0.00	0
NC3	3846	0.55	55	1.33	0.27	29	3	0.3	30	0.0	0.3	25	0.1	0.1	10	25	0.0	0.2	0	0.01	0.01	1
NC4	2858	0.41	41	1.67	0.33	36	3	0.3	30	0.0	0.1	8	0.0	0.0	4	8	0.2	0.2	20	0.27	0.27	27
NC5	2465	0.35	35	1.33	0.27	29	0	0.0	0	0.0	0.0	0	0.0	0.1	5	5	0.0	0.2	0	0.10	0.10	10
NC6	2224	0.32	32	2.00	0.40	43	3	0.3	30	0.1	0.5	49	0.1	0.1	7	49	0.2	0.2	20	0.00	0.00	0
NC7	1343	0.19	19	2.00	0.40	43	0	0.0	0	0.0	0.0	0	0.0	0.1	6	6	1.0	0.2	100	1.00	1.00	100
NC8	1321	0.19	19	3.00	0.60	64	7	0.7	72	0.1	0.4	37	0.1	0.2	17	37	0.2	0.2	20	0.01	0.01	1
NC9	1311	0.19	19	2.33	0.47	50	7	0.7	72	0.0	0.3	35	0.1	0.1	15	35	0.2	0.2	20	0.01	0.01	1
NC10	1001	0.14	14	3.67	0.73	79	7	0.7	72	0.0	0.1	9	0.1	0.1	13	13	0.0	0.2	0	0.02	0.02	2
NC11	998	0.14	14	1.67	0.33	36	7	0.7	72	0.0	0.1	14	0.6	0.9	94	94	0.2	0.2	20	0.00	0.00	0
NC12	985	0.14	14	2.67	0.53	57	10	1.0	100	0.0	0.1	12	0.1	0.1	8	12	0.0	0.2	0	0.51	0.51	51
NC13	858	0.12	12	2.00	0.40	43	3	0.3	30	0.1	0.8	82	0.2	0.3	30	82	0.0	0.2	0	0.16	0.16	16
NC14	816	0.12	12	1.67	0.33	36	3	0.3	30	0.1	0.6	58	0.0	0.1	6	58	1.0	0.2	100	0.18	0.18	18
NC15	749	0.11	11	-	-	0	7	0.7	72	0.0	0.1	7	0.2	0.3	27	27	0.0	0.2	0	1.00	1.00	100
NC16	719	0.10	10	-	-	0	0	0.0	0	0.0	0.2	17	0.0	0.1	5	17	0.0	0.2	0	0.00	0.00	0
NC17	703	0.10	10	3.67	0.73	79	3	0.3	30	0.0	0.0	3	0.1	0.1	8	8	0.0	0.2	0	1.00	1.00	100
NC18	649	0.09	9	3.00	0.60	64	7	0.7	72	0.0	0.3	28	0.1	0.1	13	28	0.0	0.2	0	0.98	0.98	98
NC19	548	0.08	8	2.33	0.47	50	7	0.7	72	0.1	0.7	71	0.1	0.1	11	71	0.0	0.2	0	0.05	0.05	5
NC20	527	0.08	8	2.33	0.47	50	7	0.7	72	0.0	0.0	2	0.7	1.0	100	100	0.2	0.2	20	0.00	0.00	0
NC21	520	0.07	7	2.33	0.47	50	10	1.0	100	0.0	0.2	17	0.0	0.0	5	17	0.0	0.2	0	0.07	0.07	7
NC22	0	-	-	-	-	0	10	1.0	100	0.0	0.1	6	0.0	0.0	0	6	0.0	0.2	0	0.00	0.00	0
NC23	467	0.07	7	4.67	0.93	100	0	0.0	0	0.1	0.5	53	0.0	0.1	6	53	0.2	0.2	20	0.97	0.97	97
NC24	459	0.07	7	2.00	0.40	43	3	0.3	30	0.1	0.5	53	0.1	0.1	10	53	0.4	0.2	40	0.54	0.54	54
NC25	426	0.06	6	3.33	0.67	71	3	0.3	30	0.0	0.2	24	0.1	0.1	10	24	0.0	0.2	0	0.90	0.90	90
NC26	418	0.06	6	-	-	0	3	0.3	30	0.0	0.0	4	0.0	0.0	5	5	0.0	0.2	0	0.62	0.62	62
NC27	0	-	-	-	-	0	10	1.0	100	0.0	0.2	21	0.0	0.0	0	21	0.0	0.2	0	0.00	0.00	0
NC28	413	0.06	6	2.00	0.40	43	3	0.3	30	0.0	0.0	5	0.1	0.2	16	16	1.0	0.2	100	0.01	0.01	1
NC29	388	0.06	6	3.33	0.67	71	7	0.7	72	0.0	0.1	7	0.0	0.1	6	7	0.0	0.2	0	0.00	0.00	0
NC30	383	0.05	5	4.00	0.80	86	10	1.0	100	0.0	0.1	9	0.1	0.1	9	9	0.0	0.2	0	1.00	1.00	100
NC31	265	0.04	4	2.00	0.40	43	0	0.0	0	0.0	0.1	5	0.0	0.0	5	5	0.0	0.2	0	0.99	0.99	99
NC32	229	0.03	3	3.33	0.67	71	0	0.0	0	0.0	0.1	6	0.0	0.1	5	6	0.0	0.2	0	0.97	0.97	97
NC33	223	0.03	3	2.33	0.47	50	10	1.0	100	0.1	1.0	100	0.1	0.2	18	100	0.4	0.2	40	0.99	0.99	99
NC34	221	0.03	3	4.67	0.93	100	7	0.7	72	0.1	0.6	62	0.1	0.1	12	62	0.0	0.2	0	0.76	0.76	76
NC35	212	0.03	3	-	-	0	0	0.0	0	0.0	0.3	31	0.0	0.1	5	31	0.0	0.2	0	1.00	1.00	100

NC	X	Y
NC1	53	20
NC2	53	40
NC3	38	25
NC4	35	8
NC5	21	5
NC6	35	49
NC7	21	6
NC8	52	37
NC9	47	35
NC10	55	13
NC11	40	94
NC12	57	12
NC13	28	82
NC14	26	58
NC15	27	27
NC16	3	17
NC17	40	8
NC18	48	28
NC19	43	71
NC20	43	100
NC21	52	17
NC22	33	6
NC23	36	53
NC24	26	53
NC25	36	24
NC26	12	5
NC27	33	21
NC28	26	16
NC29	49	7
NC30	64	9
NC31	16	5
NC32	25	6
NC33	51	100
NC34	58	62
NC35	1	31

Appendix III – Cost of Quality Cost Categories

1.0	Prevention Costs
1.1	Marketing/Customer/User
1.1.1	Marketing Research
1.1.2	Customer/User Perception Surveys/Clinics
1.1.3	Contract/Document Review
1.2	Product/Service/Design Development
1.2.1	Design Quality Progress Reviews
1.2.2	Design Support Activities
1.2.3	Product Design Qualification Test
1.2.4	Service Design - Qualification
1.2.5	Field Trials
1.3	Purchasing Prevention Costs
1.3.1	Supplier Reviews
1.3.2	Supplier Rating
1.3.3	Purchase Order Tech Data Reviews
1.3.4	Supplier Quality Planning
1.4	Operations (Manufacturing or Service) Prevention Costs
1.4.1	Operations Process Validation
1.4.2	Operation Quality Planning
1.4.2.1	Design and Development of Quality Measurement and Control Equipment
1.4.3	Operations Support Quality Planning
1.4.4	Operator Quality Education
1.4.5	Operator SPC/Process Control
1.5	Quality Administration
1.5.1	Administrative Salaries
1.5.2	Administrative Expenses
1.5.3	Quality Program Planning
1.5.4	Quality Performance Reporting
1.5.5	Quality Education
1.5.6	Quality Improvement
1.5.7	Quality System Audits
1.6	Other Prevention Costs
1.7	Investment in prevention projects

2.0	Appraisal Cost
2.1	Purchasing Appraisal Cost
2.1.1	Receiving or Incoming Inspections and Tests
2.1.2	Measurement Equipment
2.1.3	Qualification of Supplier Product
2.1.4	Source Inspection and Control Programs
2.2	Operations (Manufacturing or Service) Appraisal Costs
2.2.1	Planned Operations Inspections, Tests, Audits
2.2.1.1	Checking Labor
2.2.1.2	Product or Service Quality Audits
2.2.1.3	Inspection and Test Materials
2.2.2	Set-UP Inspections and Tests
2.2.3	Special Tests (Manufacturing)
2.2.4	Process Control Measurements
2.2.5	Laboratory Support
2.2.6	Measurement (Inspection and Test) Equipment
2.2.6.1	Depreciation Allowances
2.2.6.2	Measurement Equipment Expenses
2.2.6.3	Maintenance and Calibration Labor
2.2.7	Outside Endorsements and Certifications
2.3	External Appraisal Costs
2.3.1	Field Performance Evaluation
2.3.2	Special Product Evaluations
2.3.3	Evaluation of Field Stock and Spare Parts
2.4	Review of Test and Inspection Data
2.5	Miscellaneous Quality Evaluations
2.6	Investments in appraisal projects

3.0	Internal Failure Costs
3.1	Product/Service Design Failure Costs (Internal)
3.1.1	Design Corrective Action
3.1.2	Rework Due to Design Changes
3.1.3	Scrap Due to Design Changes
3.1.4	Production Liaison Costs
3.2	Purchasing Failure Costs
3.2.1	Purchasing Material Reject Disposition Costs
3.2.2	Purchasing Material Replacement Costs
3.2.3	Supplier Corrective Action
3.2.4	Rework of Supplier Rejects
3.2.5	Uncontrolled Material Losses
3.3	Operations (Product or Service) Failure Costs
3.3.1	Material Review and Corrective Action Costs
3.3.1.1	Disposition Costs
3.3.1.2	Troubleshooting or Failure Analysis Costs (Operations)
3.3.1.3	Investigation Support Costs
3.3.1.4	Operations Corrective Action
3.3.2	Operations Rework and Repair Costs
3.3.2.1	Rework
3.3.2.2	Repair
3.3.3	Reinspection/Retest Costs
3.3.4	Extra Operations
3.3.5	Scrap Costs (Operations)
3.3.6	Downgraded End-Product or Service
3.3.7	Internal Failure Labor Losses
3.4	Other Internal Failure Costs
3.5	Scrap collection
3.6	Scrap selection

4.0	External Failure Costs
4.1	Complaint Investigations/Customer or User Service
4.2	Returned Goods
4.3	Retrofit Goods
4.3.1	Recall Costs
4.4	Warranty Claims
4.5	Liability Costs
4.6	Penalties
4.7	Customer/User Goodwill (integrated at 4.4)
4.8	Lost Sales
4.9	Other External Failure Costs

Appendix IV – Estimation of Detection Rates

Instructions:

Please evaluate every single Nonconformity (NC) acording to the likelihood of being detected by the VIs when inspected as today. Please estimate on a scale of 0-10 (steps of 0,1 are possible) (0 = not detectable; 10 = always detectable) every single NC as presented below.

Furthermore, please indicate the medium, upper and lower bound. This means...
Medium: the majority detects a specific NC with x%;
lower bound: less good VIs detect with y%;
Upper bound: good VIs detect with z%;

NC	Detection level	NC	Detection level
NC1	7.00	NC19	2.85
NC2	7.00	NC20	7.00
NC3	7.00	NC21	2.85
NC4	7.00	NC22	10.00
NC5	2.85	NC23	0.00
NC6	7.00	NC24	0.00
NC7	10.00	NC25	7.00
NC8	2.85	NC26	10.00
NC9	2.85	NC27	7.00
NC10	0.00	NC28	2.85
NC11	10.00	NC29	10.00
NC12	0.00	NC30	10.00
NC13	2.85	NC31	0.00
NC14	7.00	NC32	7.00
NC15	7.00	NC33	7.00
NC16	0.00	NC34	10.00
NC17	7.00	NC35	2.85
NC18	2.85		

Appendix V – Results of NC Prioritization

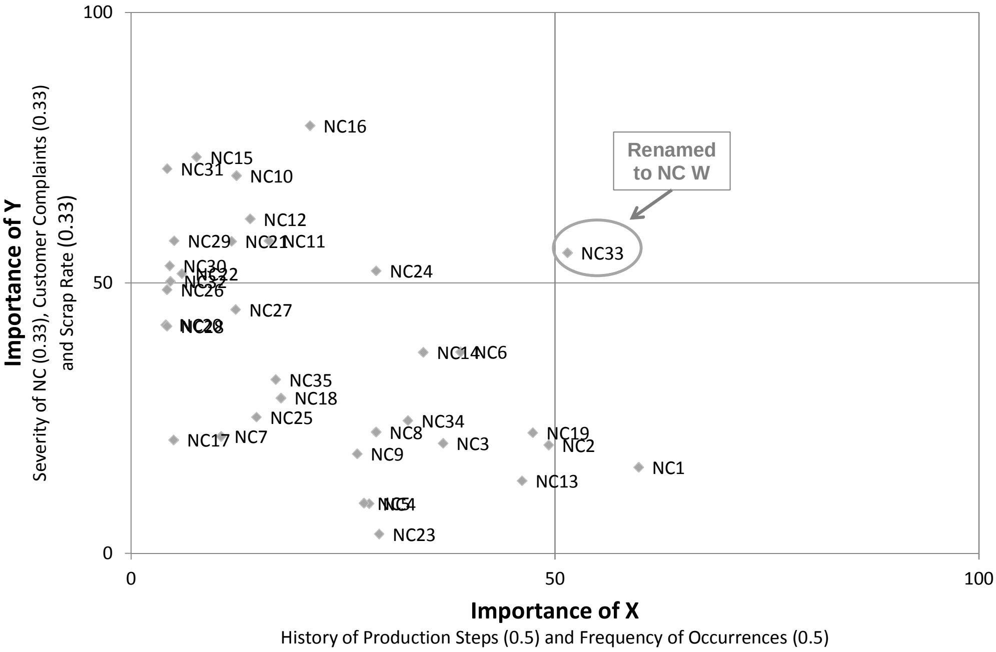

Figure 81: Average weights of the attributes of the prioritization tool.

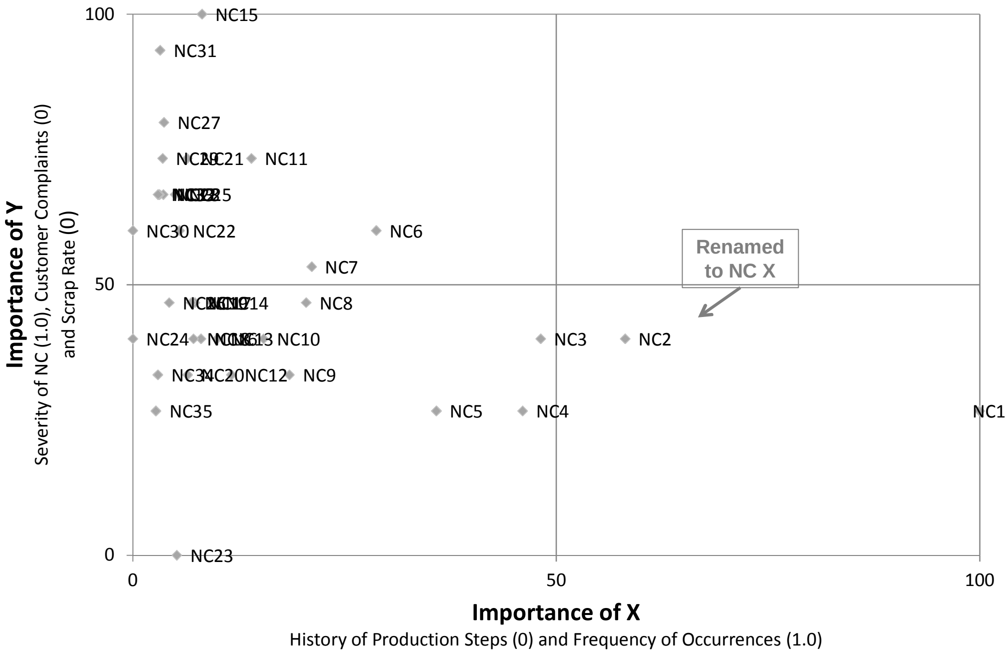

Figure 82: Severe NC with a high occurrence.

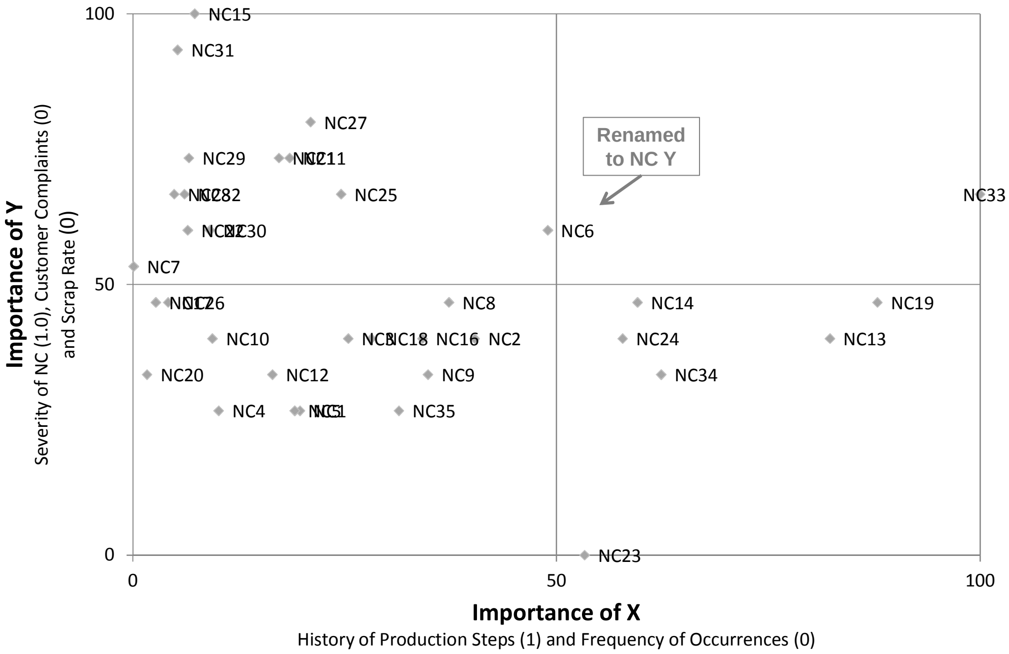

Figure 83: Severe NC with high concentration to single machines.